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LaRC DESIGN ANALYSIS REPORT

FOR

NATIONAL TRANSONIC FACILITY

FOR

9% NICKEL TUNNEL SHELL

FINITE ELEMENT ANALYSIS OF CORNERS #3 AND #4

VOL. 2

BY

JAMES W. RAMSEY, JR., JOHN T. TAYLOR, JOHN F. WILSON, CARL E. GRAY, JR., ANNE D. LEATHERMAN, JAMES R. ROOKER, AND JOHNNY W. ALLRED

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16. Abstract This report contains the results of extensive computer (finite element, finite difference and numerical integration), thermal, fatigue, and special analyses of critical portions of a large pressurized, cryogenic wind tunnel (National Transonic Facility). The computer models, loading and boundary conditions are described. Graphic capability was used to display model geometry, section properties, and stress results. A stress criteria is presented for evaluation of the results of the analyses. Thermal analyses were performed for major critical and typical areas. Fatigue analyses of the entire tunnel circuit is presented.

The major computer codes utilized are: SPAR - developed by Engineering Information Systems, Inc. under NASA Contracts NAS8-30536 and NAS1-13977; SALORS - developed by Langley Research Center and described in NASA TN D-7179; and SRA - developed by Structures Research Associates under NASA Contract NAS1-10091; "A General Transient Heat-Transfer Computer Program for Thermally Thick Walls" developed by Langley Research Center and described in NASA TM X-2058.

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NTF TUNNEL SHELL

NASA LaRC

FINITE ELEMENT ANALYSIS

OF

CORNERS #3 AND #4

9% Ni

SEPTEMBER 1976

VOLUME 2

LaRC CALCULATIONS

FOR THE

NATIONAL TRANSONIC FACILITY

TUNNEL SHELL

DATE: SEPTEMBER, 1976

APPROVED: James W. Ramsey Jr.
DR. JAMES W. RAMSEY, JR., HEAD
STRUCTURAL ENGINEERING SECTION

ANALYSTS:

John T. Taylor
JOHN T. TAYLOR
HEAD SHELL ANALYST

John F. Wilson
JOHN F. WILSON, SHELL WORK
PACKAGE & CONSTRUCTION MANAGER

Carl E. Gray, Jr.
CARL E. GRAY, JR.
SHELL ANALYST

Anne D. Leatherman
ANNE D. LEATHERMAN
SHELL PROGRAMMER

James R. Rooker
JAMES R. ROOKER
SHELL/THERMAL ANALYST

Johnny W. Allred
JOHNNY W. ALLRED
SHELL/THERMAL ANALYST

This report is one volume of a Design Analysis Report prepared by LaRC on portions of the pressure shell for the National Transonic Facility. This report is to be used in conjunction with reports prepared under NASA Contract NAS1-13535(c) by the Ralph M. Parsons Company (Job Number 5409-3 dated September 1976) and Fluidyne Engineering Corporation (Job Number 1060 dated September 1976). The volumes prepared by LaRC are listed below:

1. Finite Difference Analysis of Cone/Cylinder (9% Ni), Vol. 1, NASA TM X73956-1.

2. Finite Element Analysis of Corners #3 and #4 (9% Ni), Vol. 2, NASA TM X73956-2.

3. Finite Element Analysis of Plenum Region Including Side Access Reinforcement, Side Access Door and Angle of Attack Penetration (9% Ni), Vol. 3, NASA TM X73956-3.

4. Thermal Analysis (9% Ni), Vol. 4, NASA TM X73956-4.

5. Finite Element and Numerical Integration Analyses of the Bulkhead Region (9% Ni), Vol. 5, NASA TM X73956-5.

6. Fatigue Analysis (9% Ni), Vol. 6, NASA TM X73956-6.

7. Special Studies (9% Ni), Vol. 7, NASA TM X73956-7.

NTF DESIGN CRITERIA
FOR 9% NICKEL

GENERAL

THE DESIGN OF THE PRESSURE SHELL REFLECTED IN THIS REPORT SATISFIES THE DESIGN REQUIREMENTS OF THE ASME BOILER AND PRESSURE VESSEL CODE, SECTION VIII, DIVISION 1. SINCE DIVISION 1 DOES NOT CONTAIN RULES TO COVER ALL DETAILS OF DESIGN, ADDITIONAL ANALYSES WERE PERFORMED IN AREAS HAVING COMPLEX CONFIGURATIONS SUCH AS THE CONE CYLINDER JUNCTIONS, THE GATE VALVE BULKHEADS, THE BULKHEAD-SHELL ATTACHMENTS, THE PLENUM ACCESS DOORS AND REINFORCEMENT AREAS, THE ELLIPTICAL CORNER SECTIONS, AND THE FIXED REGION (RING S8) OF THE TUNNEL. THE DIVISION 1 DESIGN CALCULATIONS, THE ADDITIONAL ANALYSES AND THE CRITERIA FOR EVALUATION OF THE RESULTS OF THE ADDITIONAL ANALYSES TO ENSURE COMPLIANCE WITH THE INTENT OF DIVISION 1 REQUIREMENTS ARE CONTAINED IN THE TEXT OF THIS REPORT. THE DESIGN ANALYSES AND ASSOCIATED CRITERIA CONSIDERED BOTH THE OPERATING AND HYDROSTATIC TEST CONDITIONS.

IN CONJUNCTION WITH THE DESIGN, A DETAILED FATIGUE ANALYSIS OF THE PRESSURE SHELL WAS ALSO PERFORMED UTILIZING THE METHODS OF THE ASME CODE, SECTION VIII, DIVISION 2.

MATERIAL

THE PRESSURE SHELL MATERIAL SHALL BE ASME, SA-553-1 FOR PLATE AND SA-522 FOR FORGINGS. THE MATERIAL PROPERTIES AT TEMPERATURES EQUAL TO OR BELOW 150°F ARE AS FOLLOWS:

(A) PLATE, 2.0 INCHES OR THINNER

YIELD = 85.0 KSI
ULTIMATE = 100 KSI

(B) WELDS (AUTOMATIC AND SEMIAUTOMATIC)

YIELD = 52.5 KSI
ULTIMATE = 95.0 KSI

(C) WELDS (HAND)

YIELD = 58.5 KSI
ULTIMATE = 95.0 KSI

OPERATING, DESIGN AND TEST CONDITIONS

THE OPERATING, DESIGN AND TEST CONDITIONS FOR THE TUNNEL PRESSURE SHELL AND ASSOCIATED SYSTEMS AND ELEMENTS ARE SUMMARIZED BELOW:

1. OPERATING MEDIUM

   ANY MIXTURE OF AIR AND NITROGEN

2. DESIGN TEMPERATURE RANGE

   MINUS 320 DEGREES FAHRENHEIT TO PLUS 150 DEGREES FAHRENHEIT, EXCEPT IN THE REGION OF THE PLENUM BULKHEADS AND GATE VALVES INSIDE A 23-FOOT, 4-INCH DIAMETER, FOR WHICH THE TEMPERATURE RANGE IS MINUS 320 DEGREES FAHRENHEIT TO PLUS 200 DEGREES FAHRENHEIT.

3. PRESSURE RANGE

	TUNNEL CONFIGURATION	OPERATING PRESSURE RANGE, PSIA	DESIGN PRESSURES PSID
A.	CONDITION I - PLENUM ISOLATION GATES OPEN AND TUNNEL OPERATING:		
	TUNNEL CIRCUIT EXCEPT PLENUM	8.3 to 130	A. 8 EXTERNAL B. 119 INTERNAL
	PLENUM (PLENUM PRESSURE IS LIMITED TO .4 TO 1 TIMES THE REMAINDER OF THE TUNNEL CIRCUIT	3.3 to 130	A. 15 EXTERNAL B. 119 INTERNAL
	BULKHEAD		56 (EXTERNAL TO PLENUM)
B.	CONDITION II - PLENUM ISOLATION GATES OPEN AND TUNNEL SHUTDOWN:		
	ENTIRE TUNNEL CIRCUIT	8.3 to 130	A. 8 EXTERNAL B. 119 INTERNAL
	BULKHEAD		0

C. CONDITION III - PLENUM ISOLATION GATES AND ACCESS DOORS CLOSED:		
TUNNEL CIRCUIT EXCEPT PLENUM	8.3 to 130	A. 8 EXTERNAL B. 119 INTERNAL
PLENUM (PLENUM OPERATING PRESSURE CAN EXCEED THE PRESSURE IN THE REMAINDER OF THE TUNNEL CIRCUIT BY 24 PSI, BUT DOES NOT EXCEED THE 130 PSIA MAXIMUM OPERATING PRESSURE)	0 to 130	A. 15 EXTERNAL B. 119 INTERNAL
BULKHEAD		A. 25 (INTERNAL TO PLENUM) B. 119 (EXTERNAL TO PLENUM) FOR MINUS 320 DEGREES FAHRENHEIT TO PLUS 150 DEGREES FAHRENHEIT *C. 110.5 (EXTERNAL TO PLENUM) FOR PLUS 151 DEGREES FAHRENHEIT TO PLUS 200 DEGREES FAHRENHEIT

*OPERATING PROCEDURES LIMIT PRESSURES TO THAT SHOWN.

D. CONDITION IV - PLENUM ISOLATION GATES CLOSED AND ACCESS DOORS OPEN:		
TUNNEL CIRCUIT EXCEPT PLENUM	8.3 to 130	A. 8 EXTERNAL B. 119 INTERNAL
PLENUM	14.7	0
BULKHEAD		A. 119 (EXTERNAL TO PLENUM) FOR MINUS 320 DEGREES FAHRENHEIT TO PLUS 150 DEGREES FAHRENHEIT *B. 110.5 (EXTERNAL TO PLENUM) FOR PLUS 151 DEGREES FAHRENHEIT TO PLUS 200 DEGREES FAHRENHEIT

*OPERATING PROCEDURES LIMIT PRESSURES TO THAT SHOWN.

4. HYDROSTATIC TEST DESIGN CONDITIONS

THE PRESSURE SHELL WAS DESIGNED FOR HYDROSTATIC TEST IN ACCORDANCE WITH THE REQUIREMENTS OF THE ASME CODE, SECTION VIII, DIVISION 1. THE TEST PRESSURES SHALL BE AS FOLLOWS. PRESSURE SHELL TEMPERATURE SHALL BE EQUAL TO OR BELOW 100°F DURING HYDROSTATIC TESTS.

CONDITION (1) - MAXIMUM INTERNAL PRESSURE CONDITION FOR THE ENTIRE TUNNEL CIRCUIT

$$PH_1 = 1.5\ (119) + \text{HYDROSTATIC HEAD}$$
$$= 178.5\ \text{PSI} + \text{HYDROSTATIC HEAD}$$

CONDITION (2) - MAXIMUM DIFFERENTIAL PRESSURE CONDITION ACROSS THE PLENUM BULKHEADS

$$PH_2 = 1.5\ (119) + \text{HYDROSTATIC HEAD}$$
$$= 178.5 + \text{HYDROSTATIC HEAD}$$

$$PH_2{*} = 1.5\ (111.5)\ \left(\frac{23.7}{22.2}\right) + \text{HYDROSTATIC HEAD}$$

$$= 178.5 + \text{HYDROSTATIC HEAD}$$

*TUNNEL OPERATION LIMITATIONS PRECLUDE PRESSURE DIFFERENTIALS ACROSS BULKHEADS IN EXCESS OF 110.5 PSI FOR BULKHEAD AND GATE TEMPERATURES IN EXCESS OF 150°F.

CONDITION (3) - MAXIMUM REVERSE DIFFERENTIAL PRESSURE CONDITION ACROSS THE PLENUM BULKHEADS

$$PH_3 = 1.5\ (25) = 37.5\ \text{PSI}$$

THE PRESSURE SHELL EXCEPT FOR THE PLENUM SHALL BE PRESSURIZED TO 141 PSIG. THE PLENUM SHALL BE PRESSURIZED TO 178.5 PSIG.

PRESSURE SHELL STRESS EVALUATION CRITERIA

THIS CRITERIA ESTABLISHES THE BASIS FOR ANALYSIS AND DESIGN OF THE PRESSURE SHELL SO IT WILL MEET OR EXCEED ALL OF THE REQUIREMENTS OF SECTION VIII, DIVISION 1 OF THE ASME BOILER AND PRESSURE VESSEL CODE AND CAN BE STAMPED WITH A DIVISION 1 "U" STAMP.

1. SECTION VIII, DIVISION 1, DIRECT APPLICATION

A. THE MAXIMUM ALLOWABLE STRESS (S)

$S = 23.7$ KSI (-320°F TO +150°F)

$S = 22.2$ KSI (-320°F TO +200°F)

(B) PRIMARY BENDING PLUS PRIMARY MEMBRANE STRESSES

THE LOCAL MEMBRANE STRESSES ARE NOT GENERALLY CONSIDERED IN SECTION VIII, DIVISION 1 DESIGNS. HOWEVER, FOR THE PURPOSE OF DESIGNING LOCAL REINFORCEMENT AT BRACKETS, RINGS OR PENETRATIONS NOT COVERED BY DESIGN BASED ON STRESS ANALYSIS, THE LOCAL SHELL MEMBRANE STRESS SHALL BE:

$$P_b + P_m \leq 1.5 \text{ SE}$$

NOTE: E IS JOINT EFFICIENCY

2. IN REGIONS OF THE PRESSURE SHELL WHERE DIVISION 1 DOES NOT CONTAIN RULES TO COVER ALL DETAILS OF DESIGN (REF. U-2(g)), ADDITIONAL ANALYSES WERE PERFORMED UTILIZING THE GUIDELINES OF THE ASME CODE, SECTION VIII, DIVISION 2, APPENDIX 4, "DESIGN BASED ON STRESS ANALYSIS." THE BASIC STRESS CRITERIA FOR DIVISION 2 IS REPRESENTED IN FIGURE 4-130.1 AND RESTATED BELOW INDICATING ANY MODIFICATIONS OR EXCESS REQUIREMENTS APPLIED TO IT TO REMAIN WITHIN THE INTENT OF DIVISION 1 AND TO OBTAIN A DIVISION 1 STAMP.

A. GENERAL PRINCIPAL MEMBRANE STRESS

MAXIMUM ALLOWABLE STRESS

$S = 23.7$ KSI (-320°F TO +150°F)

$S = 22.2$ KSI (-320°F TO +200°F)

MAXIMUM ALLOWABLE STRESS INTENSITY

$S_m = 31.7$ KSI (-320°F TO +200°F)

B. PRIMARY GENERAL MEMBRANE STRESS INTENSITY

$$P_m \leq S_m$$

AND IN ORDER TO COMPLY WITH DIVISION 1, THE MAXIMUM PRINCIPAL MEMBRANE STRESS MUST BE:

$$P_m^* \leq S$$

NOTE: THE * IS USED TO DENOTE THAT MAXIMUM PRINCIPAL STRESSES ARE TO BE COMPUTED FOR THE GIVEN LOADING CONDITION. THE INTENT IS TO DETERMINE THE STRESSES WHICH REPRESENT THE HOOP STRESSES AND MERIDIONAL STRESSES WHICH ARE THE STRESSES USED IN DIVISION 1 COMPUTATIONS.

C. DESIGN LOADS, PRIMARY LOCAL MEMBRANE STRESS INTENSITY

$$P_L \leq 1.5\ S_m$$

NOTE: LOCAL MEMBRANE STRESS INTENSITY IS DEFINED IN ACCORDANCE WITH DIVISION 2, APPENDIX 4-112(i). THE TOTAL MERIDIONAL LENGTH IS CONSIDERED TO BE 1.0 $\sqrt{RT}$.

D. DESIGN LOADS, PRIMARY LOCAL MEMBRANE PLUS PRIMARY BENDING STRESS INTENSITY

$$P_L + P_b \leq 1.5\ S_m$$

E. OPERATING LOADS, PRIMARY PLUS SECONDARY STRESS INTENSITY

$$P_L + P_b + Q \leq 3\ S_m$$

F. COMMENT

BECAUSE OF THE LOW YIELD STRENGTH EXPECTED AT THE WELDS AS COMPARED TO THE YIELD STRENGTH OF THE PLATE, STRESS INTENSITIES COMPUTED IN (A), (B), (C), (D), OR (E) SHALL NOT EXCEED THE YIELD STRENGTH OF THE MATERIAL AT EITHER WELD OR PLATE LOCATIONS.

3. A FATIGUE ANALYSIS WAS CONDUCTED IN ACCORDANCE WITH SECTION VIII, DIVISION 2 WITHOUT MODIFICATION.

4. HYDROSTATIC TEST CONDITION DESIGN CONSIDERATIONS

A. PRESSURE SHELL

IN ACCORDANCE WITH DIVISION 1 OF THE ASME CODE, DESIGN ANALYSIS OF THE PRESSURE SHELL FOR THE HYDROSTATIC TEST CONDITION IS NOT REQUIRED. HOWEVER, IN ORDER TO PROVIDE A SATISFACTORY ENGINEERING DESIGN FOR THE PRESSURE SHELL THE FOLLOWING CRITERIA WAS USED:

(a) THE MAXIMUM GENERAL MEMBRANE STRESS PERPENDICULAR TO A WELD LINE WAS LIMITED TO THE LESSER OF:

$$P_m * \leq 0.8 \text{ WELD YIELD STRESS}$$

OR

$$P_m * \leq 0.5 \text{ WELD ULTIMATE STRESS}$$

(b) THE GENERAL PRINCIPAL MEMBRANE STRESS IN THE PLATE (NOT AT A WELD) WAS LIMITED TO THE LESSER OF:

P_m * $\leq$ 0.8 PLATE YIELD STRESS

P_m * $\leq$ 0.5 PLATE ULTIMATE STRESS

(*) THE STRESSES SATISFYING THIS CRITERIA ARE BASED ON MAXIMUM MEMBRANE STRESSES RATHER THAN INTENSITY CRITERIA.

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CHKD. BY________ DATE__________ ____ JOB NO._______________________

Vol. 2

Finite Element Analyses of Corners No. 3 and No 4

9 % Ni

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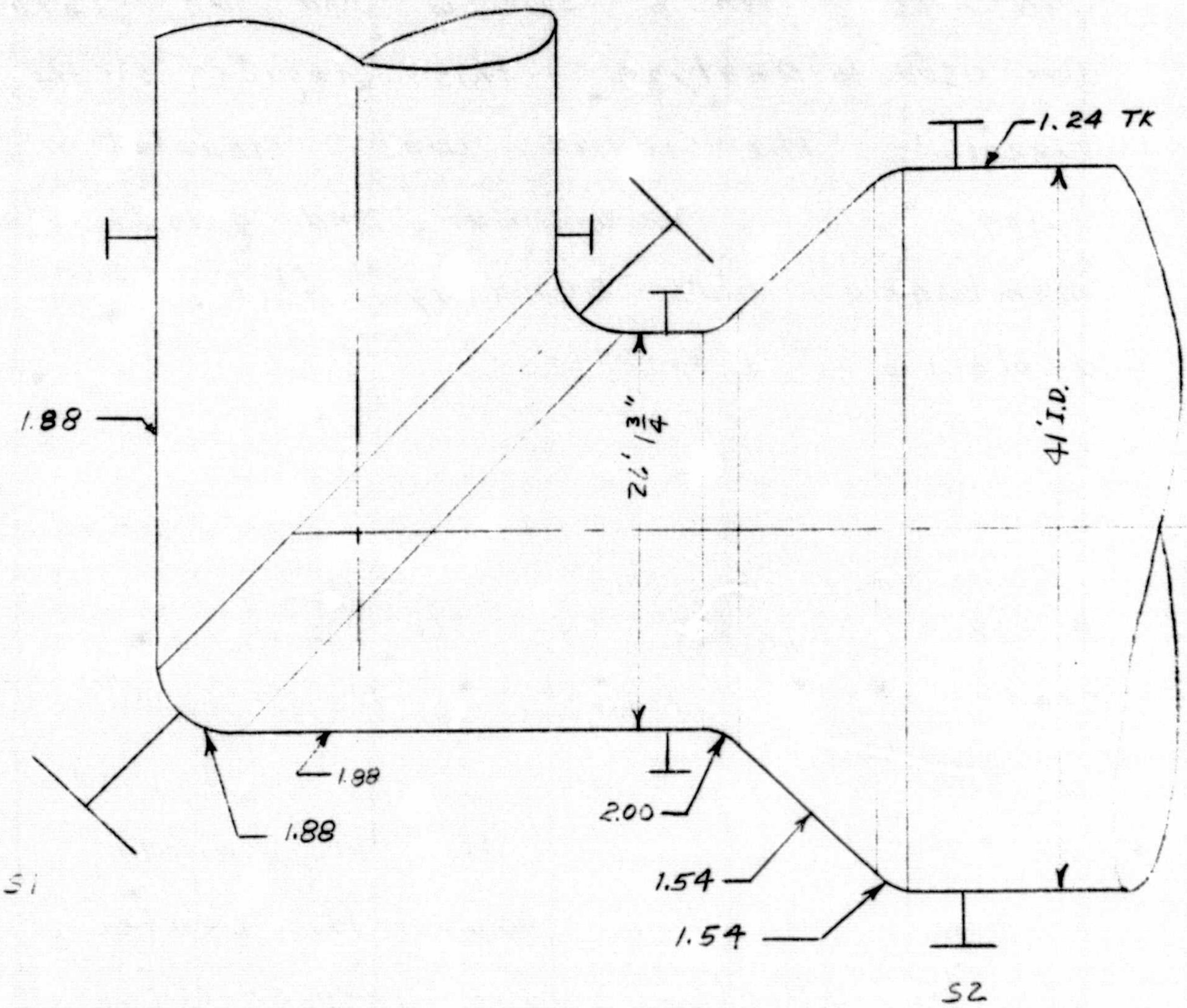
9% Ni

Reference Drawing No. LE 944383, LE 944389 & LE 944390

9% Ni



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SPAR (a finite element computer code developed & maintained by Engineering Information System, Inc. under NASA contracts NAS8-30536 and NAS1-13977) was used to analyze this region of the tunnel. The region was modeled using, triangular and quadrilateral, membrane plus bending flat aeolotropic elements.

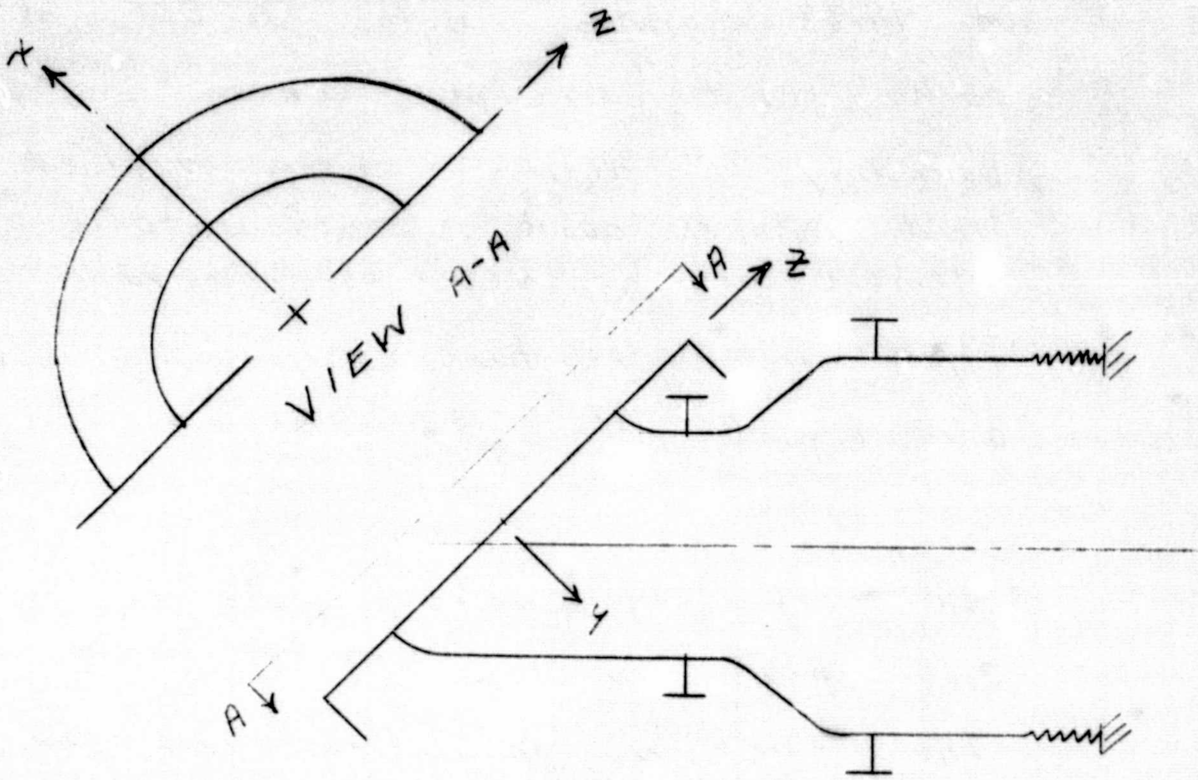
A 180° segment of the pressure shell was modeled from the center of the elliptical ring (S1) to beyond the ring (S2) on the 41' Diameter section. A plane thru the center of the elliptical ring perpendicular to the axis of rotation is a plane of symmetry. A plane thru the major axis of the ellipse is also a plane of symmetry.

Computer plots of the model are shown in figs. 1 thru 4. The model consists of 1488 joints with 6 DOF at each joint except where boundary conditions were applied and rotation about an axis ⊥ to a plate element was restricted as required. The joint numbers are shown on Figs. 5 thru 16.

Shell section properties (plate thickness) are shown in Figs. 17 thru. 22 The section properties and thickness are listed below

Shell Section Property	Thickness
1	1.25
2	1.50
3	1.88
4	1.88
5	1.88
6	0.85
7	1.24
8	1.54
9	2.00
10	1.24

Boundary Conditions



XZ plane is a plane of symmetry

YZ plane is a plane of symmetry

boundary of cylinder restricts rotation about θ and Z axes (cyl. coord.)

Boundary forces were developed by attaching linear springs (in the axial direction) to the end of the cylinder. The model was allowed to reach equilibrum and hence develop the axial forces. The spring constant was selected to approximately represent the spring constant of the cylindrical shell. However, it was found that the value of the spring constant had negligible effect on stresses.

Loadings

An internal pressure of 119 psig (design pressure) was applied as nodal pressure to the joints of the pressure surface.

Results

Nodal stresses are presented in Figs. 23 thru. 58.
The max. principal stress (PS1) or min. principal stress (PS2) are given for the Mid-surface (surface 0), the inside surface (surface 1) and outside surface (surface 2).

The stresses plotted are for joint 1 of the element. As an example (reference Fig 5), for the element defined by joints 125 126 157 156 joint 1 for that element is 125.

Nodal stresses for one joint are given from 4 elements (for quadrilateral elements). If any discrepancies exist in the stresses for a joint, the largest value is used in the interpretation of the results.

Membrane Stress Intensity

To evaluate the membrane stress intensity, the membrane stress intensity vs. meridional distance was plotted along the horizontal ℄ (ie the region of highest membrane stress)

For group 1 index 1 Joint 1

$\sigma_1 = 22.01$ KSI

$\sigma_2 = 4.09$ KSI

$\sigma_3 = -\frac{.119}{2} = .06$ KSI

$S_{12} = \sigma_1 - \sigma_2 = 22.01 - 4.09 = 17.92$ KSI

$S_{23} = \sigma_2 - \sigma_3 = 4.09 - (-.06) = 4.15$ KSI

$S_{31} = \sigma_3 - \sigma_1 = -.06 - 22.01 = -22.07$ KSI

$S = |-22.07| = 22.01$ KSI

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Table 1

Group/Ind	Joint No.	Meridional Length	S P=119
1/1	1	0	22.07
2/1	125	4.60	22.07
3/1	156	9.20	22.66
4/1	218	13.80	22.64
5/1	249	18.40	21.22
7/1	311	23.00	17.60
2/1	342	25.40	14.34
2/31	373	26.65	13.82
2/61	404	27.89	13.47
2/91	435	29.14	13.30
3/1	466	30.38	13.34
3/31	621	36.38	16.37
6/1	652	45.38	26.07
6/61	683	49.63	30.17
6/121	714	53.88	33.17
6/181	745	58.12	34.59
6/241	776	62.37	34.13
4/1	807	66.62	31.59
4/31	838	75.00	26.83

P = 119 psig

Membrane Stress

The membrane stress intensity exceeds the allowable Sm (31.7) in the region of the knuckle at the small dia. of the cone. See Fig 59.

The membrane stress intensity does not exceed 1.1 Sm (1.1 X 31.7 = 34.87)

∴ the stress is a local membrane stress intensity

34.59 < 1.5 Sm = 1.5(31.7) = 47.55 KSI

The principal membrane stresses, except for the region of the knuckle at the small dia. of the cone, do not exceed 23.7 KSI. This knuckle region is an area of local membrane stress.

∴ the general principal membrane stress does not exceed the allowable of 23.7 KSI

The primary general membrane stress intensity does not exceed the allowable stress intensity of 31.7 KSI.

∴ The membrane stress (stress intensity) meets the stress evaluation criteria.

P= 119 psig

Primary Plus Secondary Stress Intensity

Knuckle under the elliptical Ring

The max. stress intensity occured on the inside surface of the shell under the elliptical ring See fig 25

1 /24 - 12   Inside Surface (not shown on plot)

σ_1 = 61.68 KSI

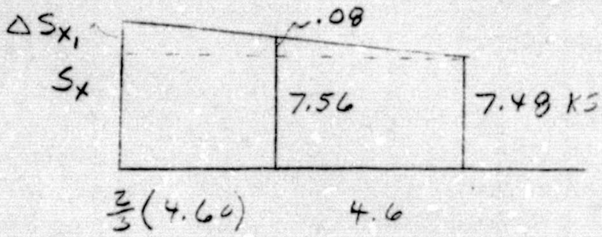
σ_2 = 19.41 KSI

σ_3 · .119 KSI

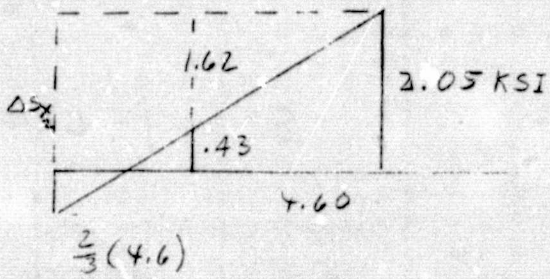
REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

The membrane stress at the nodes of triangular elements are actually the stress at the centroid of the element. Therefore interpretation is required to find the actual membrane stress at the node.

PS1



PS2



$$\frac{.08}{4.6} = \frac{\Delta S_{x_1}}{\frac{2}{3}(4.6) + 4.6} \qquad \frac{1.62}{4.60} = \frac{\Delta S_{x_2}}{\frac{2}{3}(4.60) + 4.60}$$

$$\Delta S_{x_1} = .133 \text{ KSI} \qquad \Delta S_{x_2} = 2.70$$

To correct the stress at the node add $(.133 - .08) = .053$ KSI to Max principal (PS1) and $(1.63 - 2.70) = -1.07$ to Min. principal stress to find the correct nodal stress

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$\sigma_1 = 61.68 + .053 = 61.73$ KSI

$\sigma_2 = 19.41 + -1.07 = 18.34$ KSI

$\sigma_3 = -.119$ KSI

$S_{12} = \sigma_1 - \sigma_2 = 61.73 - 18.34 = 43.43$ KSI

$S_{23} = \sigma_2 - \sigma_3 = 18.34 - (-.119) = 18.22$ KSI

$S_{31} = \sigma_3 - \sigma_2 = -.119 - 61.73 = -61.85$ KSI

$S = |-61.85| = 61.85$ KSI

For plate

61.85 KSI < 85 KSI (yield of plate)

$\therefore$ stress intensity is O.K. for the plate

For weld

61.85 > 58.5 KSI (yield of weld)

∴ stress intensity is too high for any welding in this region

The max. stress intensity for a region with welds must be limited to 52.5 KSI (auto welding)

See fig 61 for region of no longitudional weld in the knuckle

This restriction also applies to the bottom half of the knuckle

Outside Surface 1/22/11

$\sigma_1 = -18.55$ KSI

$\sigma_2 = -48.72$ KSI

$\sigma_3 = 0$

Since the max. outside stress occurs at approximately the same location as the max. inside stress, the correction for membrane stress at the node will be approximately the same as for the outside surface.

$\sigma_1 = -18.55 + 0.53 = -18.02$ KSI

$\sigma_2 = -48.72 + (-1.07) = -49.79$ KSI

$\sigma_3 = 0$

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

$S_{12} = -18.02 - (-49.79) = -31.77$ KSI

$S_{23} = -49.79 - 0 = -49.79$ KSI

$S_{31} = 0 - (-18.55) = 18.55$ KSI

$S = |-49.79| = 48.72$ KSI

$P_L + P_b + Q \leq 3S_m$

$49.79 < 52.5$ KSI (aux welds)

O.K.

∴ The primary plus secondary stress intensity of the outside surface of the region meets the stress criteria

Primary Plus Secondary Stress Intensity

Knuckle at small dia cone

Outside Surface Group 6 Index 181

$\sigma_1 = 41.68$ KSI

$\sigma_2 = 28.37$ KSI

$\sigma_3 = 0$ KSI

$S_{12} = 41.68 - 28.37 = 13.31$ KSI

$S_{23} = 28.37 - (-.0) = 28.37$ KSI

$S_{31} = -.0 - 41.68 = -41.68$ KSI

$S = |-41.68| = 41.68$ KSI

$P_L + P_b + Q < \sigma_{YP}$

$41.68 < 52.5$ KSI (auto weld)

O.K.

Inside Surface Group 6 Index 181

$\sigma_1 = 27.39$ KSI

$\sigma_2 = -13.82$ KSI

$\sigma_3 = -\frac{.119}{2} = -.06$

$S_{12} = 27.39 - (-13.82) = 41.21$ KSI

$S_{23} = -13.82 - (-.06) = -13.76$ KSI

$S_{31} = -.06 - 27.39 = -27.45$ KSI

$S = |41.21| = 41.21$ KSI

$P_L + P_b + Q < \sigma_{YP}$

$41.21 < 52.5$ KSI (auto weld)

O.K.

∴ The primary plus secondary stress intensity for this region meets the stress evaluation criteria

BY ______ DATE ______ SUBJECT ______ SHEET NO. 20 OF ______
CHKD. BY ______ DATE ______ JOB NO. ______

Knuckle region at the large dia Cyl.

See Vol. 1 Finite Element Analyses of Cone/Cylinder Junctions (R1 to S2) for evaluation of this region.

Hydro Test Conditions

The hydro test pressure was Assumed to be the max. pressure at the bottom of the tunnel at the region under consideration during hydro test.

$$P_H = 1.5(119) + \text{water head}$$

$$P_H = 1.5(119) + 62.4\,\frac{lb}{ft^3} \times \frac{1\,ft^2}{144\,in^2}\left[\frac{41\,ft}{2} + \frac{26.14\,ft}{2}\right]$$

$$P_H = 178.5 + 14.55$$

$$P_H = 193.0 \quad psi$$

Hydro stresses (Hoop direction)

Group 1 Index 1 Joint 1

$S_x = 22.01$ KSI avg. Net section stress at $P = 119$ psi

$$S_{Hx} = \frac{193}{119}(22.01) = 35.70 \text{ KSI}$$

BY ______ DATE ______ SUBJECT ______ SHEET NO. 22 OF ______
CHKD. BY ______ DATE ______ JOB NO. ______

To evaluate the hydro stresses, S_{Hx} vs. meridional distance (ℓ) was plotted along the horizontal ℄ (ie the region of highest membrane stress). See Fig 60.

BY ____________ DATE ________ SUBJECT ______________________________ SHEET NO. 23 OF ______

CHKD. BY ______ DATE ________ JOB NO. ____________

GROUP/ /INDEX	JOINT NUMBER	MERIDIONAL LENGTH	$S_{\phi x}$ P= 193
1/1	1	0	35.70
2/1	125	4.60	35.70
3/1	156	9.20	36.65
4/1	218	13.80	36.51
5/1	249	18.40	33.86
7/1	311	23.00	27.70
2/1	342	25.40	23.15
2/31	373	26.65	22.30
2/61	404	27.89	21.73
2/91	435	29.14	21.44
3/1	466	30.38	21.51
3/31	621	36.38	26.46
6/1	652	45.38	41.47
6/61	683	4963	48.53
6/121	714	53.88	53.65
6/181	745	58.12	55.99
6/241	776	62 37	55.13
4/1	807	66 62	51 14
4/31	838	75.00	43 42

For "stick" welding σ_{yp} (welds) = 58.5 KSI

σ_{ult} (welds) = 95.0 KSI

smaller of

$P_m \leq 0.8(58.5) = 46.8$ KSI

or

$P_m \leq 0.5(95.0) = 47.5$ KSI

∴ General membrane stress is limited to 46.8 KSI

The membrane stress exceeds the allowable (46.8 KSI) in the region of the knuckle at the small dia of the cone. (see Fig 60)

BY ________ DATE ________ SUBJECT ________ SHEET NO. 25 OF ______
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At a stress of

$$1.1(46.8) = 51.48 \text{ KSI}$$

The stress extends over a meridional length of 14"

$$14'' < \sqrt{RT} = \sqrt{(13.07' \times 12)(2)} = 17.7''$$

∴ The stress that exceeds 46.8 KSI is a local stress

The general membrane stress is < 46.8 KSI.

This region satisfies the stress evaluation criteria for Hydro test.
The welds in the knuckle at the small dia of the cone must be stick (σ_{yp} = 58.5 KSI) welded.

Model checks

To verify that the elements were small enough (30 elements around 180° of the circumference) to produce peak stresses, a fine element model (100 element around 180° of circumference) was developed for the knuckle region under the elliptical "T". For the fine model, boundary conditions were from the coarse model.

Note: The plate thickness has changed slightly since these check models were run.

Shell under the elliptical "T"

Peak bending Principal stress

"30 element model"	"100 element" model
61.5 KSI	61.89 KSI

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

Stress on 41' dia Section

$$\sigma_1 = \frac{Pr}{t} = \frac{(119)(20.5 \times 12 + .62)}{1.24} = 23.67 \text{ KSI}$$

$$\sigma_2 = \frac{Pr}{2t} = \frac{(119)(20.5 \times 12 + .62)}{2(1.24)} = 11.83 \text{ KSI}$$

From computer model

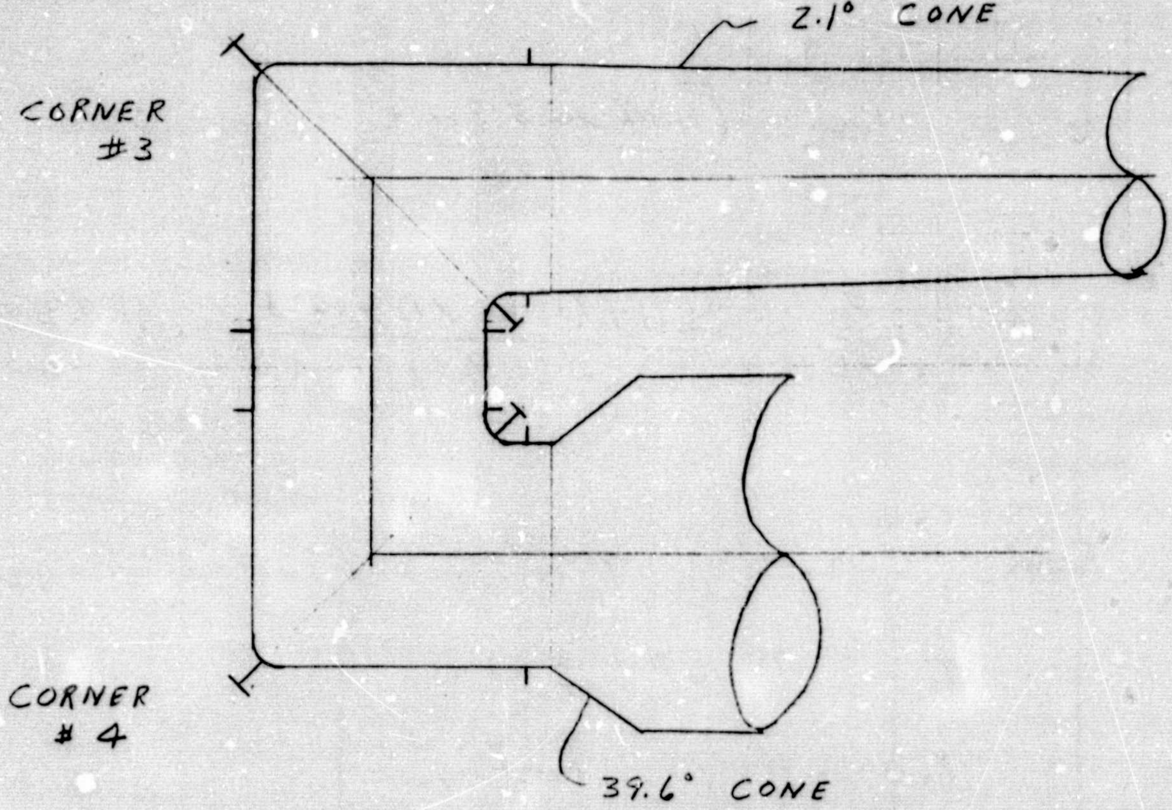
$\sigma_1 = 24.60$ KSI

$\sigma_2 = 11.78$ KSI

σ_1 is slightly high due to the effect of the "T" ring. The longitudional stress is generated correctly (11.83 vs 11.78)

∴ Model Boundary conditions are O.K.

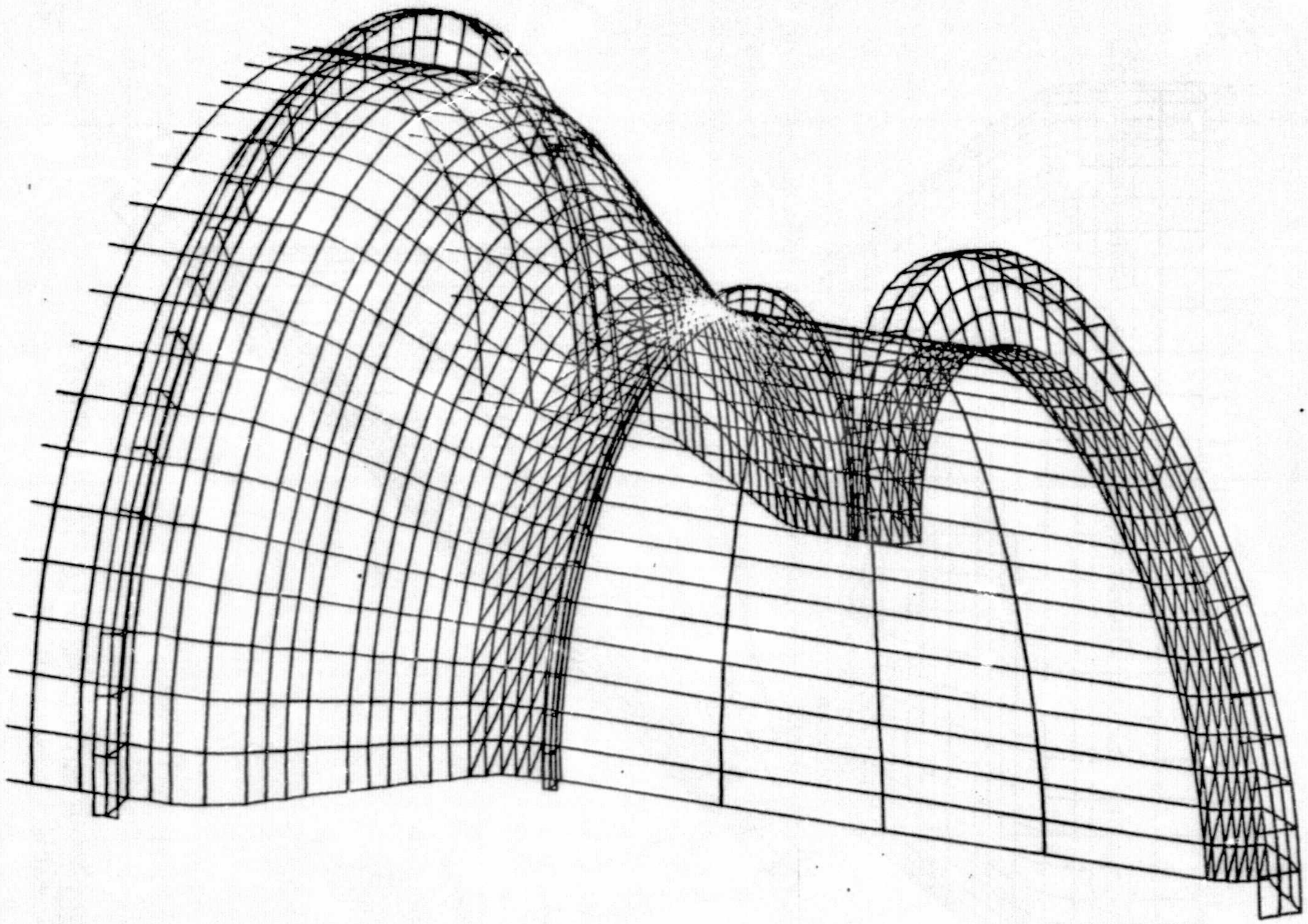
CORNER # 3



Corners No. 3 + 4 are the same except for the connecting cones. The discontinuity stresses produced by the junction of a shallow cone / cylinder are very small. (ref. Vol 1 Fig 18, 19 + 20) The approximate influence from the corner was considered in the evaluation of the stresses

BY________ DATE________ SUBJECT______________________ SHEET NO. 28 OF______
CHKD. BY______ DATE________ ______________________ JOB NO.__________

in the region between
R6 and R9 and between R10
and R12. These stresses meet
the evaluation criteria.
Since the junction at corner no. 3
will be less severe due to shallow
cone angle, this area was not
analyzed in detail.



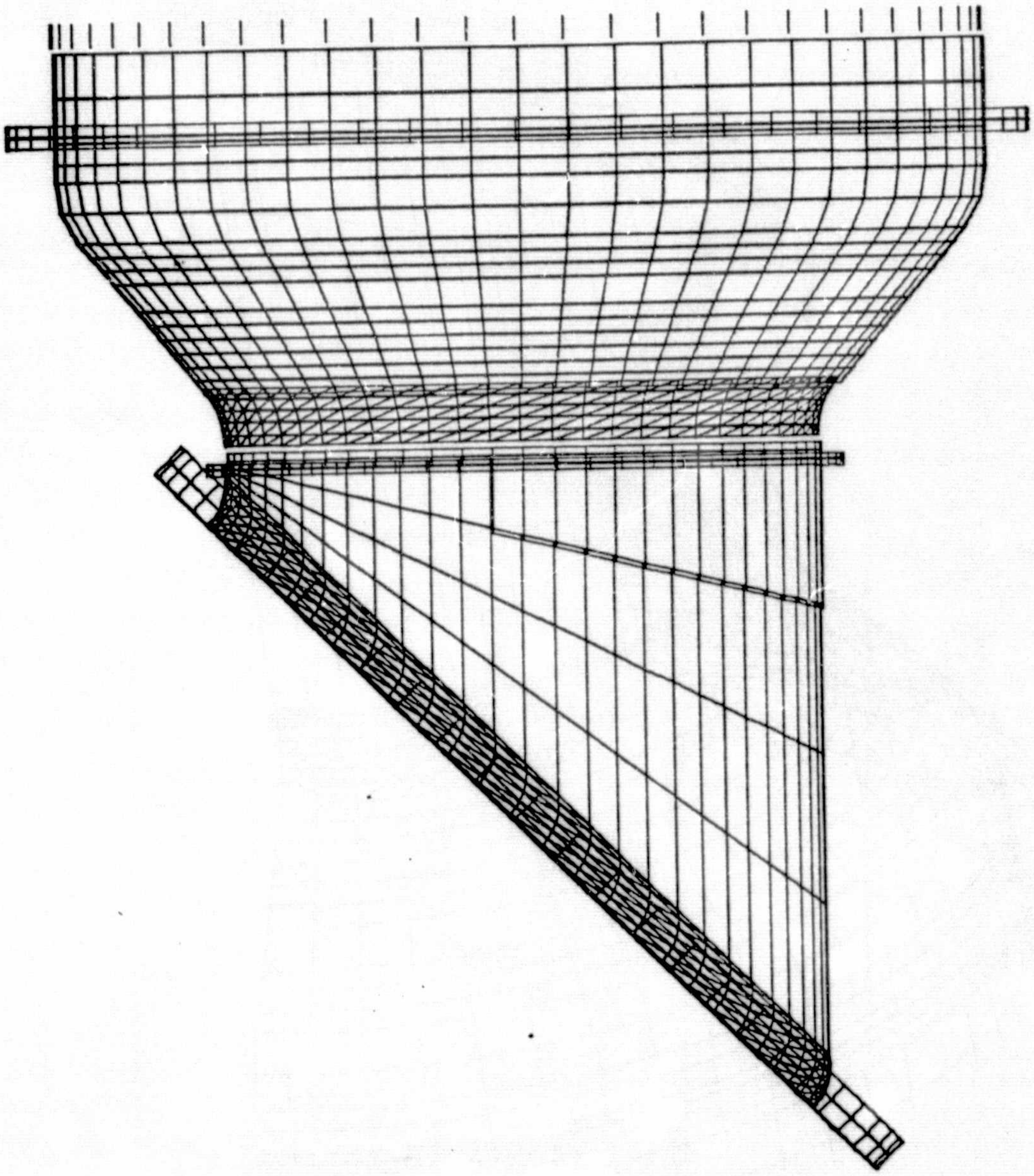
SPEC 8.1

NTF ELLIP RING CONNECTED TO 41 FT CYL
PROJECTED VIEW

0 88
SCALE

Figure 1

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR



SPEC 13.1 NTF ELLIP RING CONNECTED TO 41 FT CYL
PLAN VIEW

0 ——— 93
SCALE

Figure 2

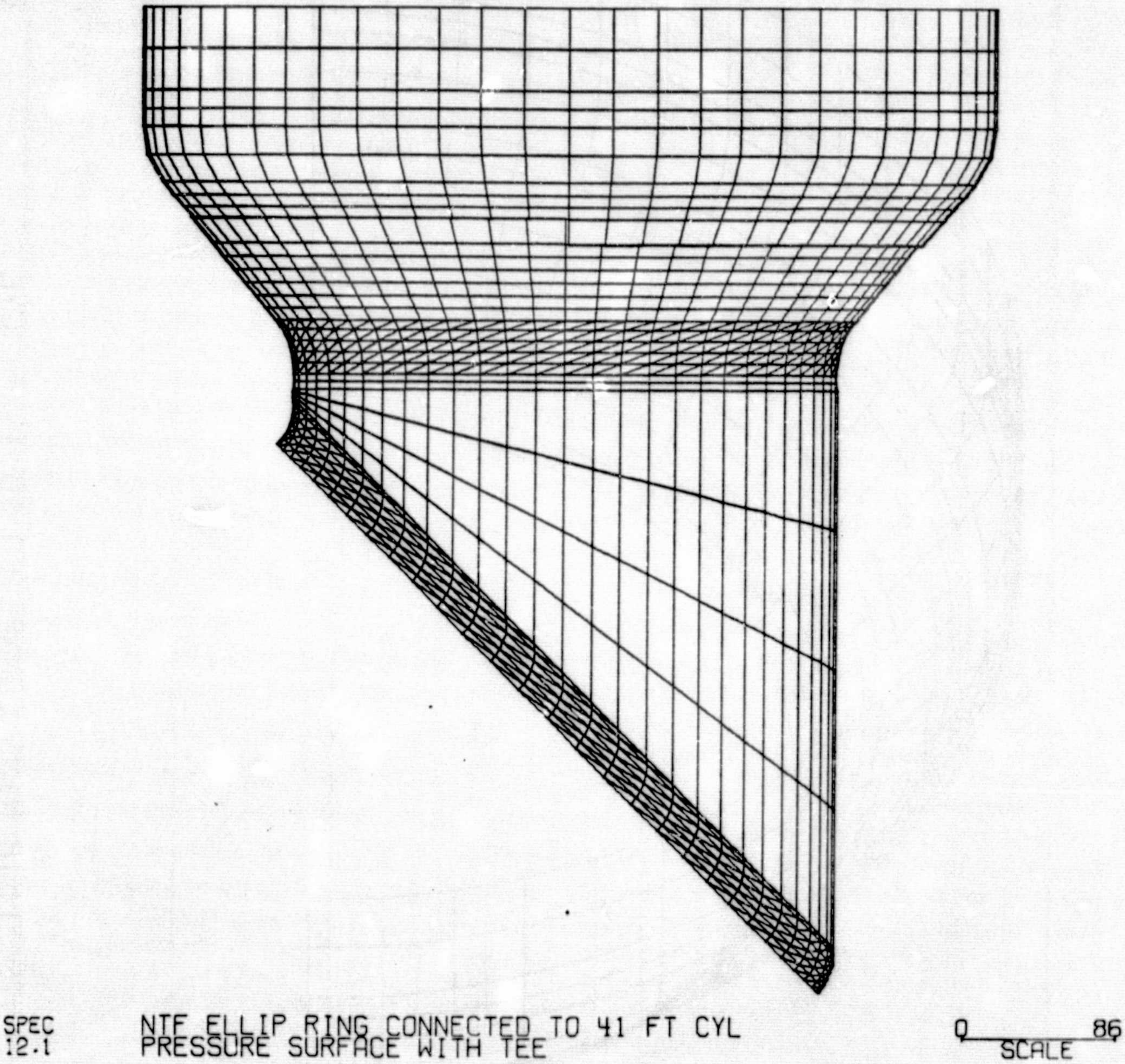
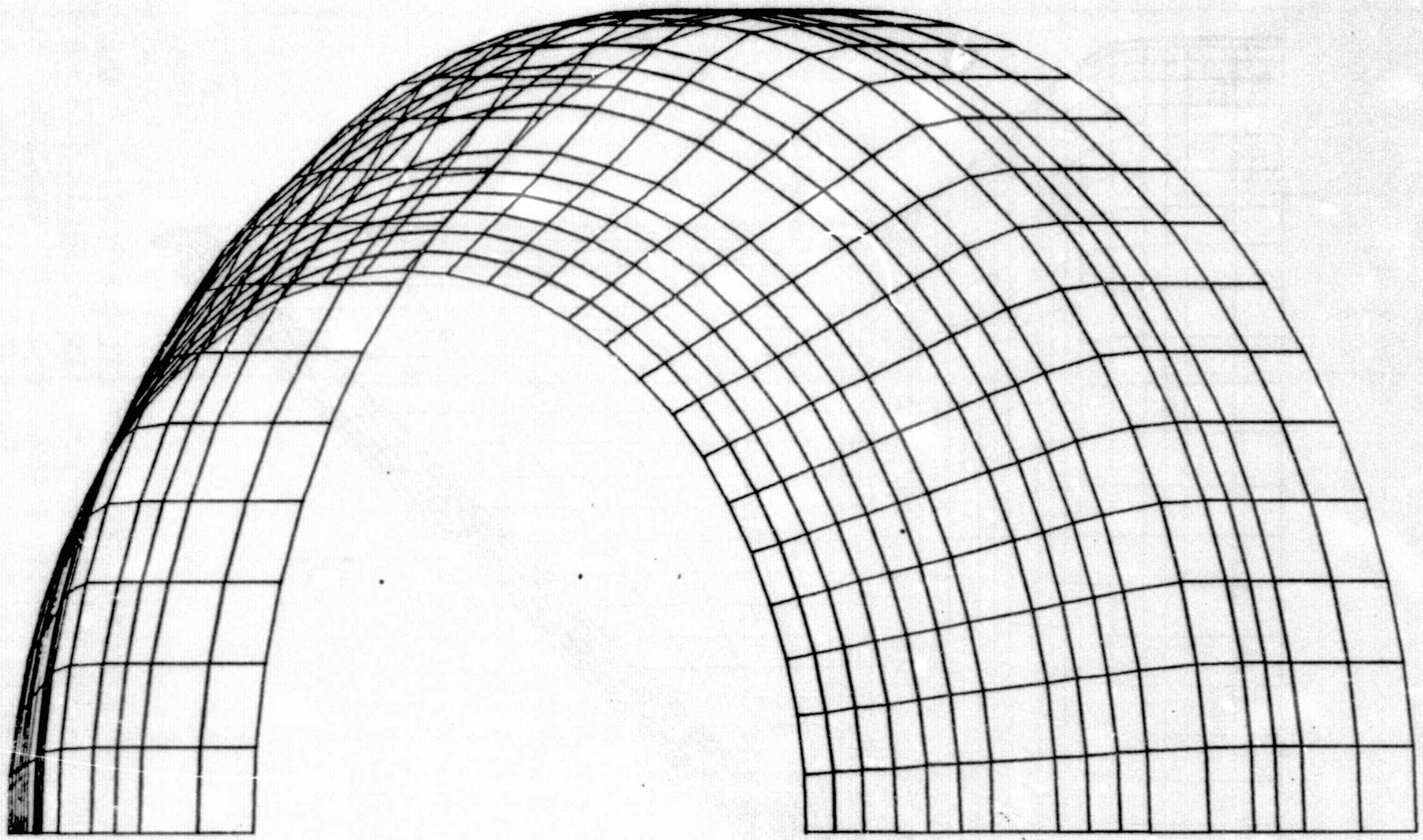

SPEC
12.1
NTF ELLIP RING CONNECTED TO 41 FT CYL
PRESSURE SURFACE WITH TEE
0
86
SCALE

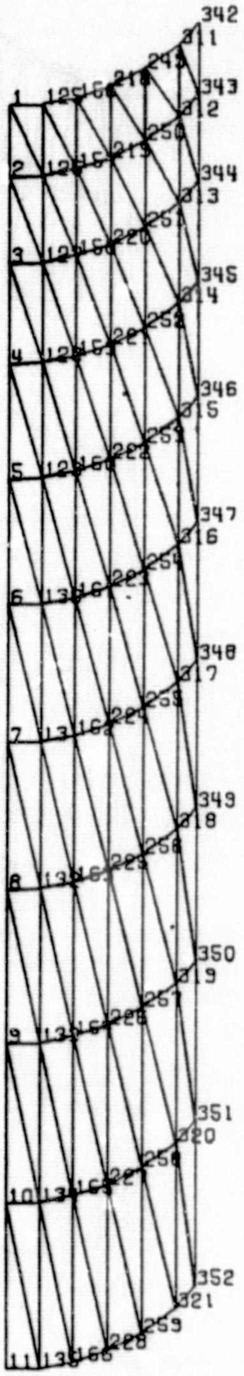
Figure 3



SPEC 7.1 NTF ELLIP RING CONNECTED TO 41 FT CYL CONE WITH SPRING B.C.

0 64
SCALE

Figure 4

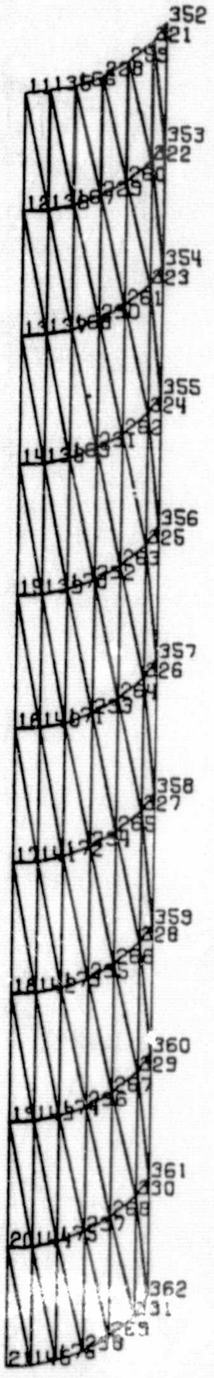


SPEC 1.1

NTF ELLIP RING CONNECTED TO 41 FT CYL
KNUCKLE SECT. AT ELLIP. RING(INS. CORNE

0 27
SCALE

Figure 5



SPEC
.1

NTF ELLIP RING CONNECTED TO 41 FT CYL
KNUCKLE SECT AT ELLIP RING (MIDDLE)

0 36
SCALE

Figure 6

REPRODUCIBILITY OF THE
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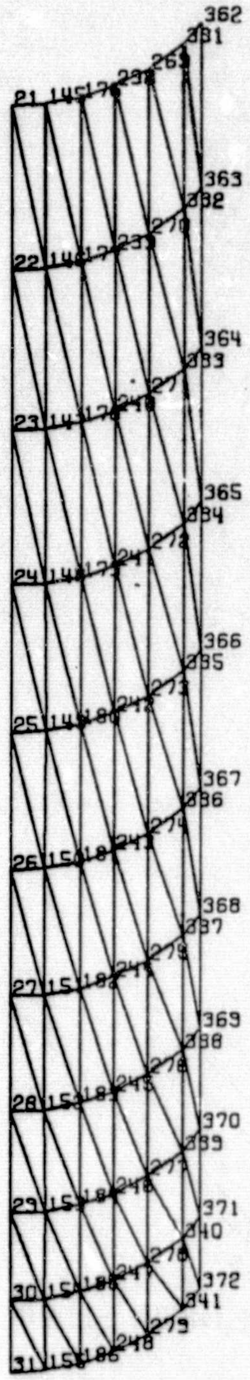
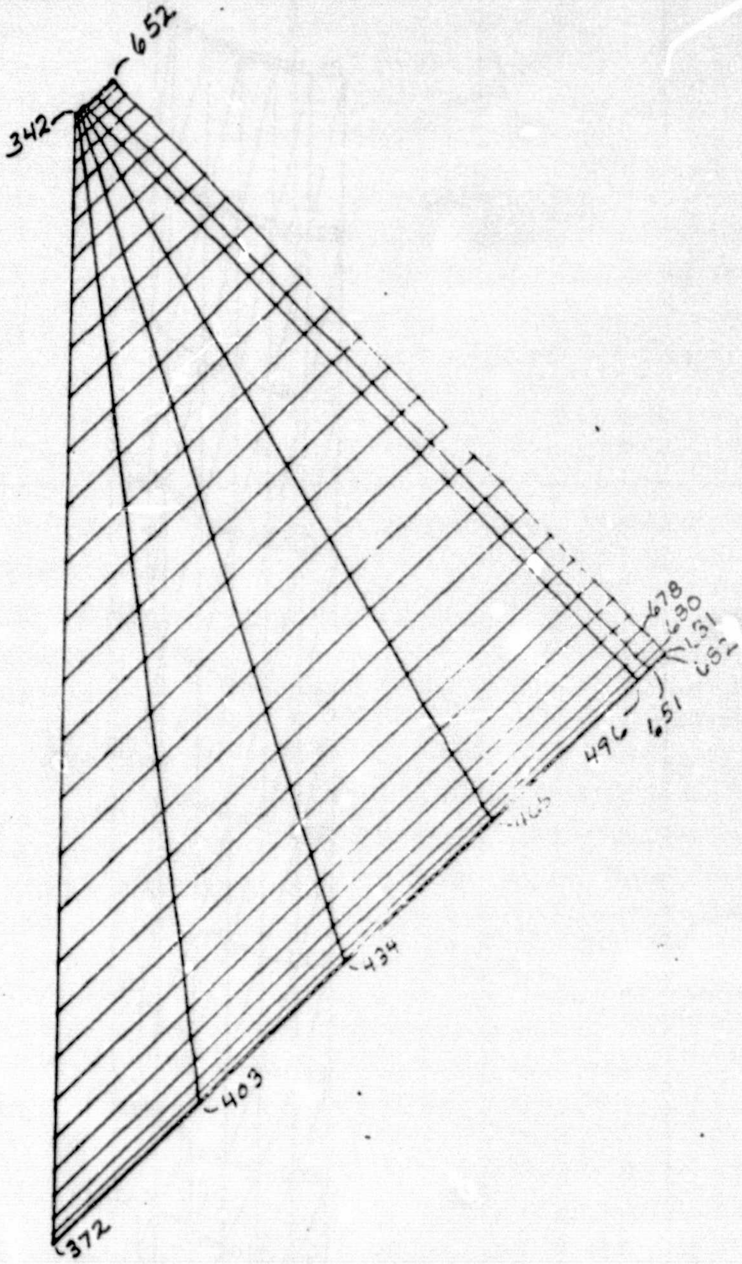


SPEC 3.1 NTF ELLIP RING CONNECTED TO 41 FT CYL
KNUCK SECT AT ELLIP RING (OUTSIDE)

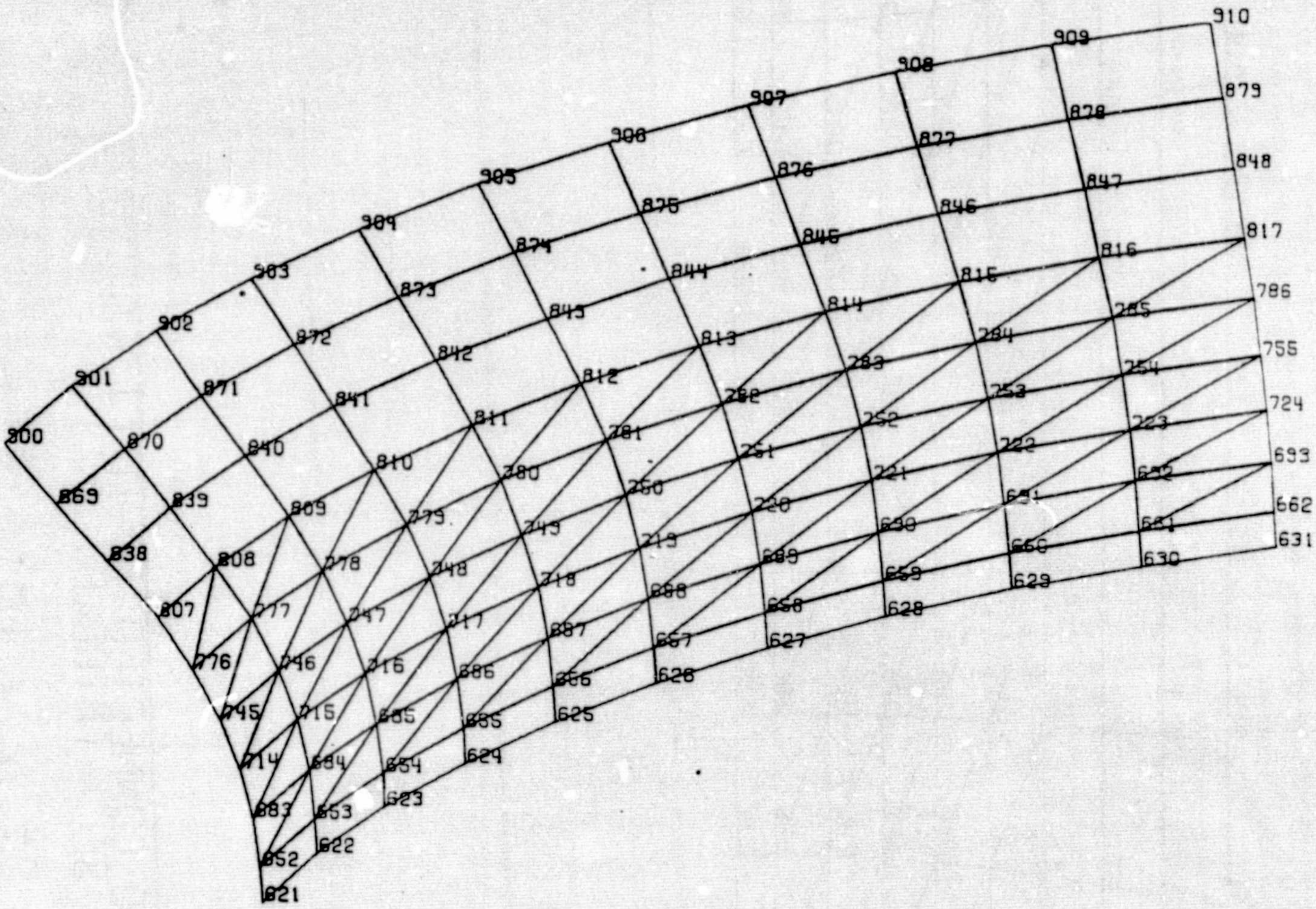
0 27
SCALE

Figure 7



SPEC 17.1 CYL SHELL BETWEEN ELLIP KNUCK - CONE

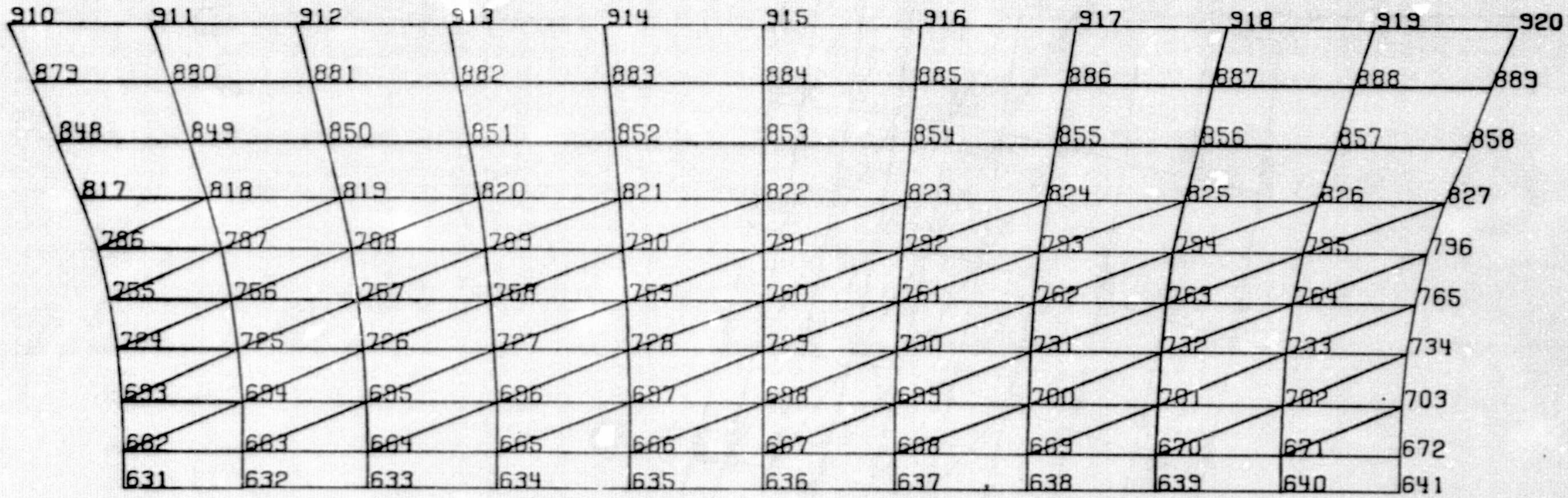
FIGURE 8



SPEC 4.1 NTF ELLIP RING CONNECTED TO 41 FT CYL
CONE KNUCKLE SECTION (INSIDE CORNER)

0 23
SCALE

Figure 9

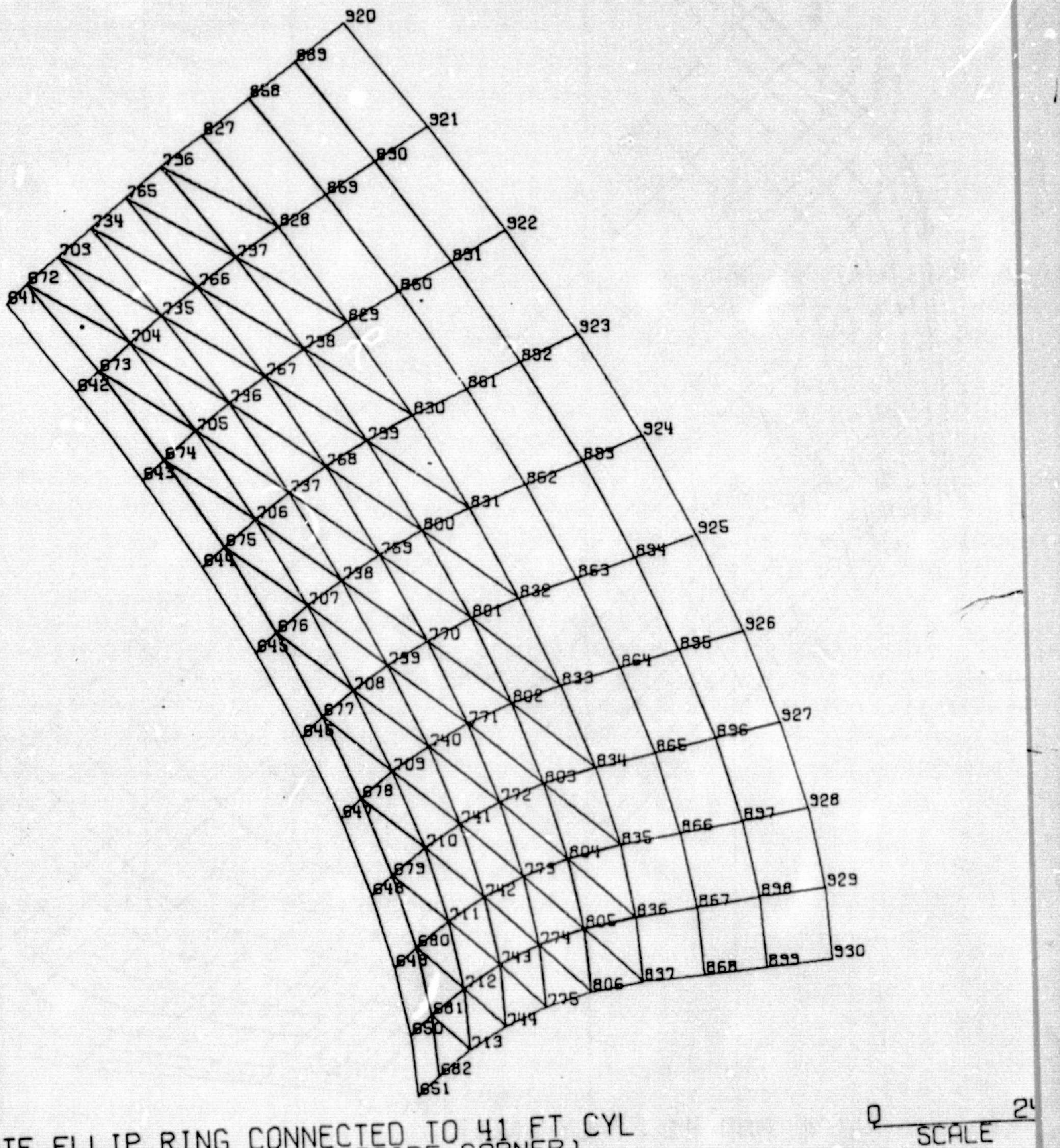


SPEC
5.1

NTF ELLIP RING CONNECTED TO 41 FT CYL
CONE KNUCKLE SECT (MIDDLE)

0 28
SCALE

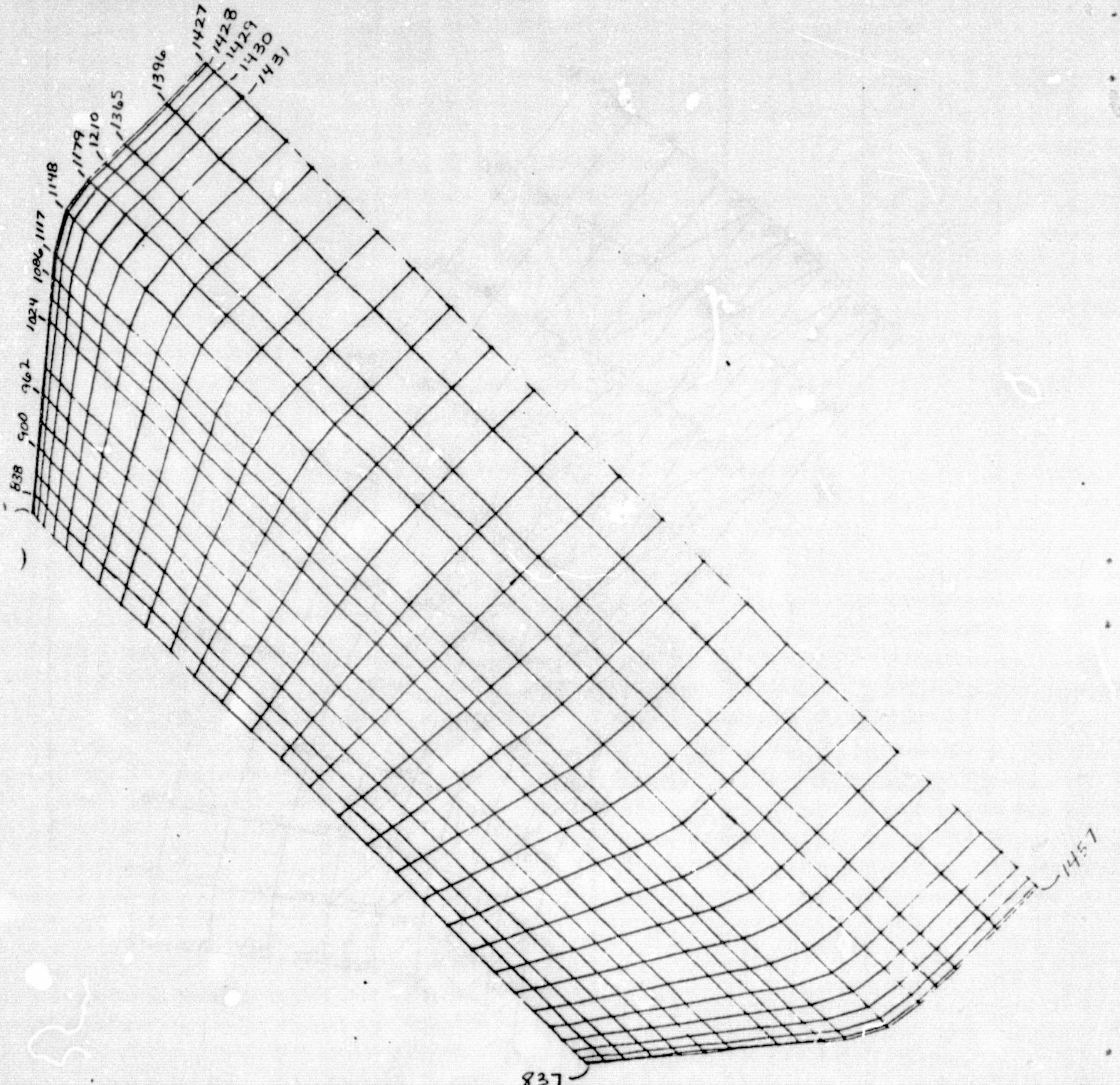
Figure 10



SPEC
6.1

NTF ELLIP RING CONNECTED TO 41 FT CYL
CONE KNUC. SECT. (OUTSIDE CORNER)

Figure 11



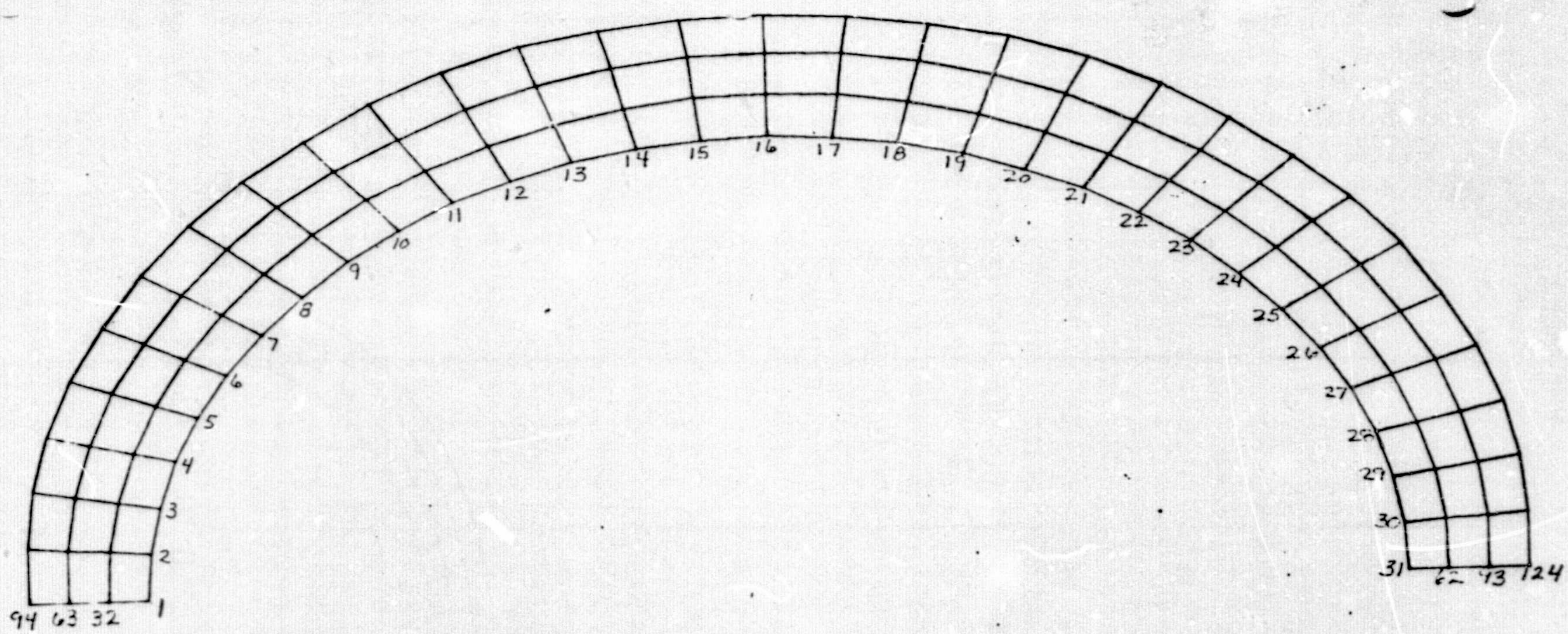
EC
.1

CONE AND 41 FT CYLINDER

0 64
SCALE

FIGURE 12

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR



SPEC
14.:

ELLIPTICAL TEE

0 81
SCALE

FIGURE 13

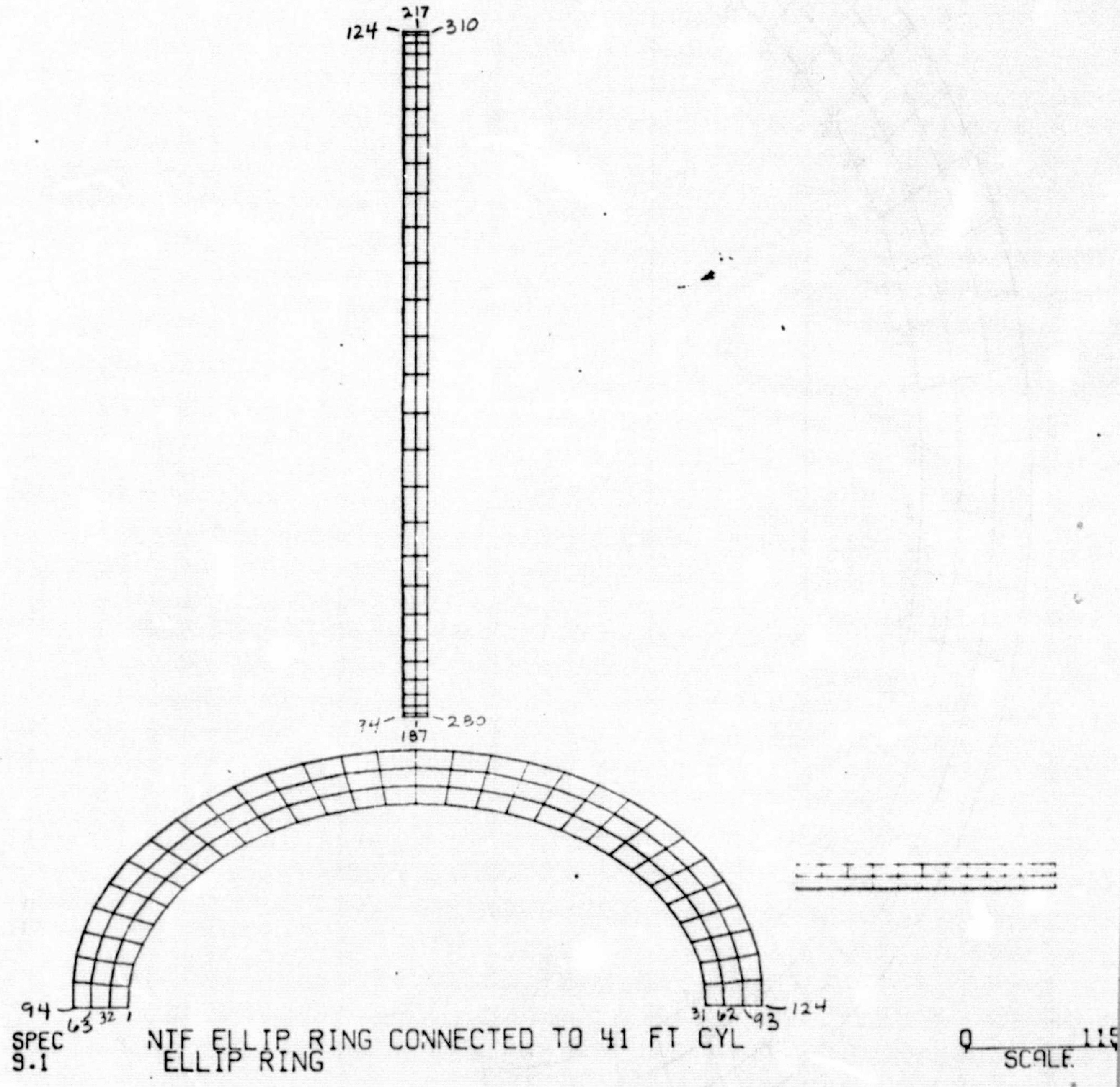

124
217
310
187
280
94
63
32
1
31
62
93
124
SPEC
9.1
NTF ELLIP RING CONNECTED TO 41 FT CYL
ELLIP RING
0
115
SCALE

FIGURE 14

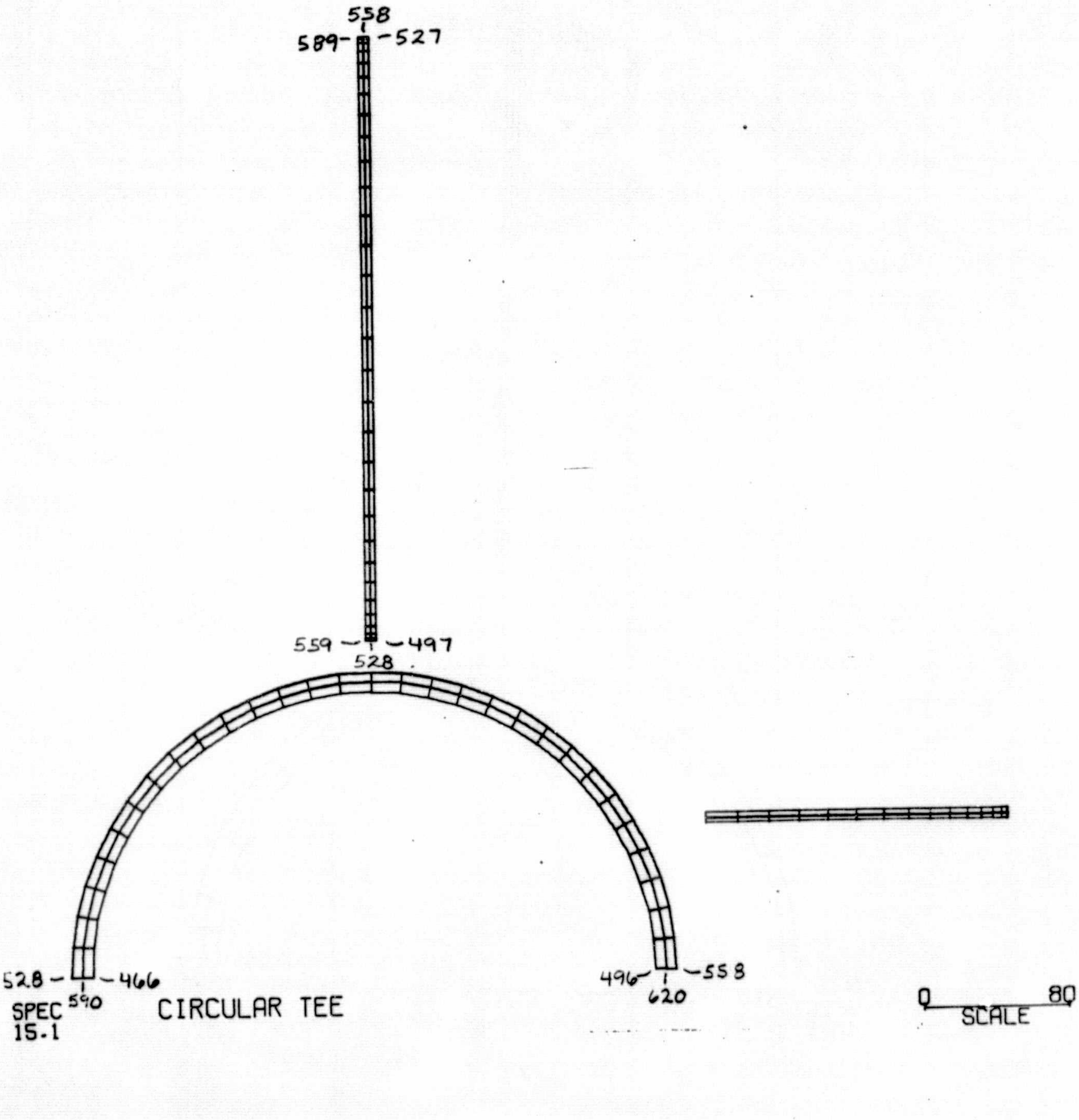
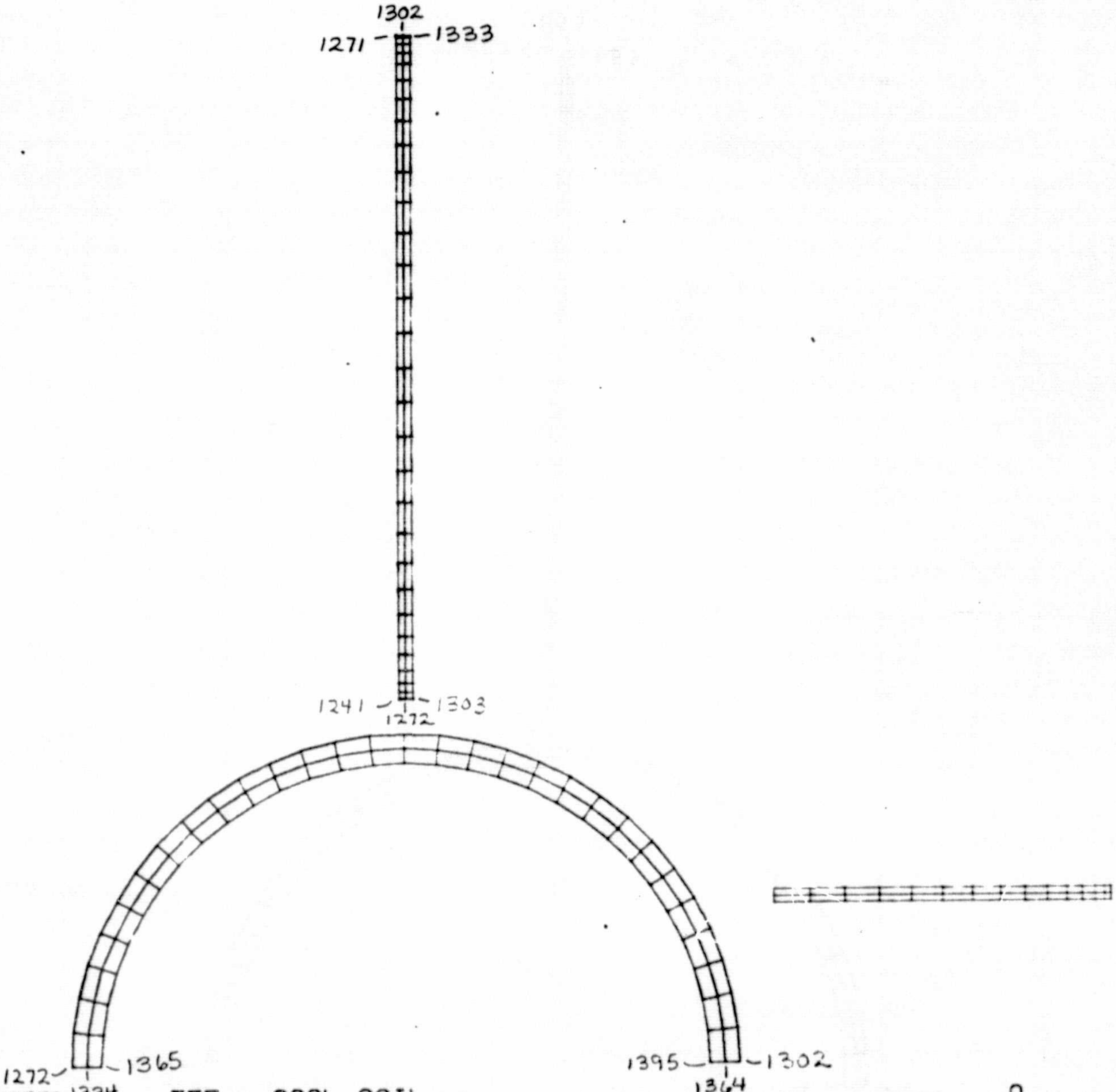

558
589
527
559
497
528
528
466
SPEC
15-1
590
CIRCULAR TEE
496
558
620
0
80
SCALE

Figure 15

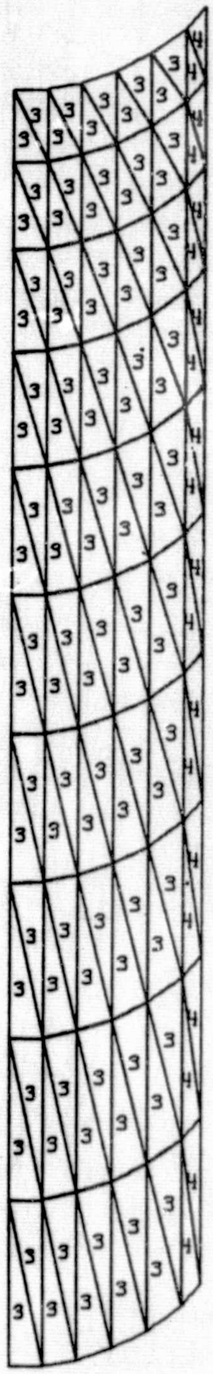


SPEC
16.1

TEE - COOL COIL

0 128
SCALE

FIGURE 16



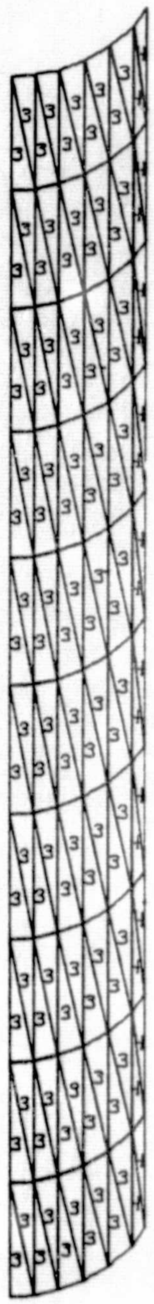
ELEMENT SECTION PROPERTY GROUPS

SPEC 1

NTF ELLIP RING CONNECTED TO 41 FT CYL
KNUCKLE SECT. AT ELLIP. RING(INS. CORNE

0 27
SCALE

Figure 17



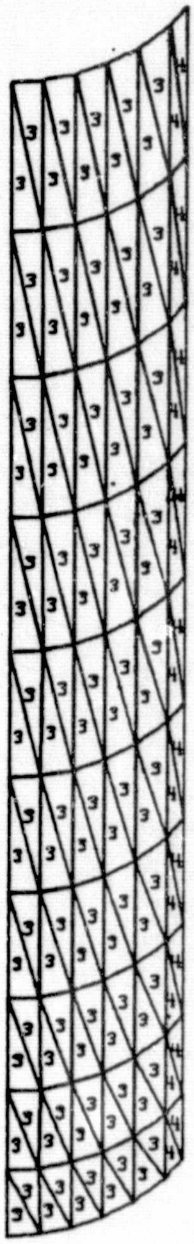
SPEC
2.1

NTF ELLIP RING CONNECTED TO 41 FT CYL
KNUCKLE SECT AT ELLIP RING (MIDDLE)

0 36
SCALE

ELEMENT SECTION PROPERTY GROUPS

Figure 18



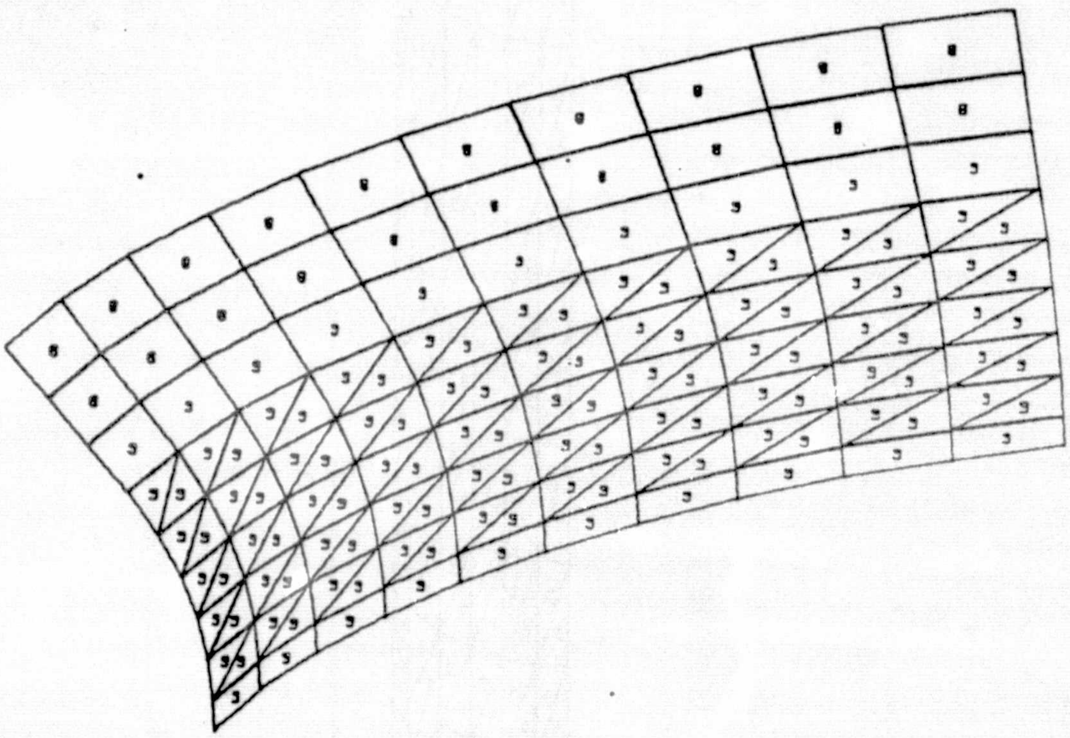
SPEC 3.1 NTF ELLIP RING CONNECTED TO 41 FT CYL
KNUCK SECT AT ELLIP RING (OUTSIDE)

0 ——— 27
SCALE

Figure 19

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

SECTION PROPERTY GROUPS

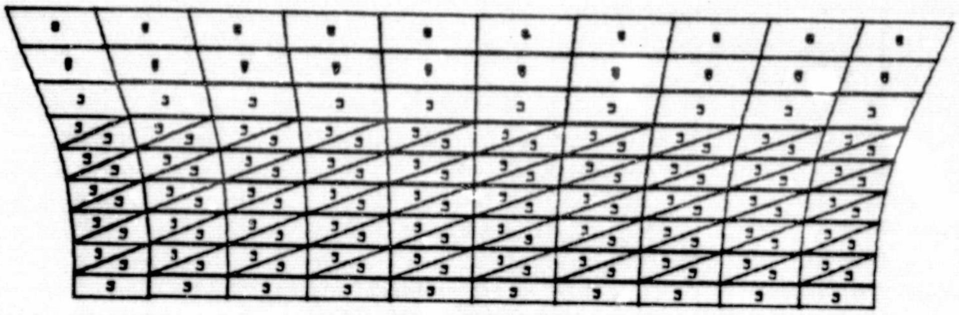


SPEC
4.1

NIF ELLIP RING CONNECTED TO 41 FT CYL
CONE KNUCKLE SECTION (INSIDE CORNER)

0 ——— 23
SCALE

Figure 20

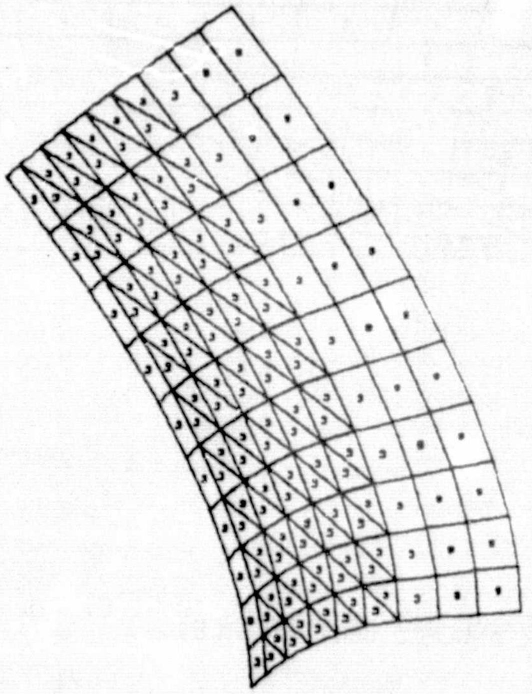


SPEC
6.1

NIF ELLIP RING CONNECTED TO 41 FT CYL
CONE KNUCKLE SECT (MIDDLE)

0 ___ 28
SCALE

Figure 21



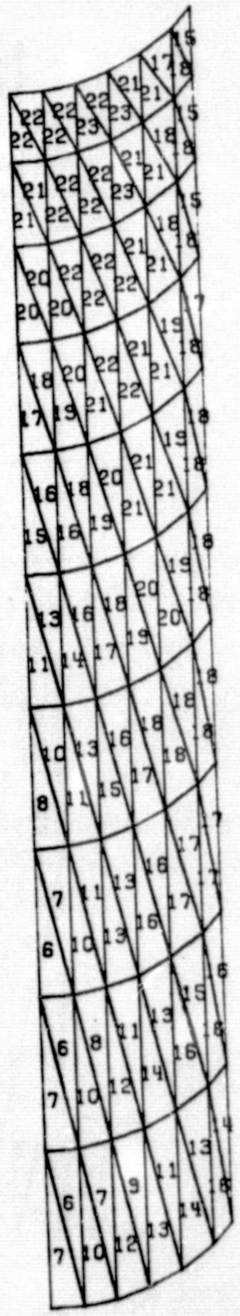
SPEC 6.1 NTF ELLIP RING CONNECTED TO 41 FT CYL
CONE KNUC. SECT. (OUTSIDE CORNER)

0 24
SCALE

Figure 22

1/1/1

DISPLAY= PS1 /1000 , NODE= 1 , SURFACE= 0



0 27
SCALE

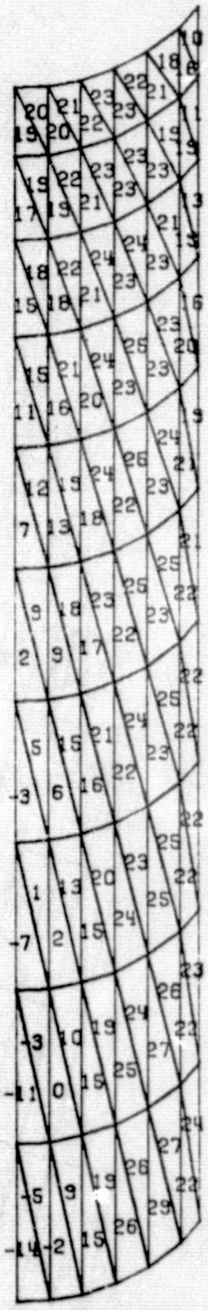
SPEC
1.1

NTF ELLIP RING CONNECTED TO 41 FT CYL
KNUCKLE SECT. AT ELLIP. RING(INS. CORNE

FIGURE 23

1/1/1

DISPLAY= PS1 /1000 , NODE= 1 , SURFACE= 1



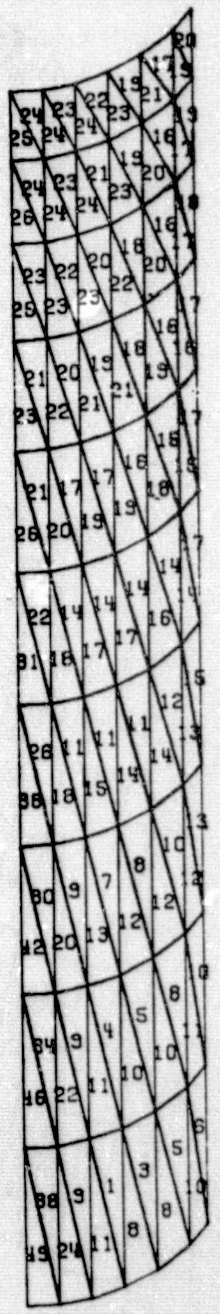
SPEC 1.1 NTF ELLIP RING CONNECTED TO 41 FT CYL
KNUCKLE SECT. AT ELLIP. RING(INS. CORNE

0 27 SCALE

FIGURE 21

1/1/1

DISPLAY= PS1 /1000 , NODE= 1, SURFACE= 2



SPEC 1.1

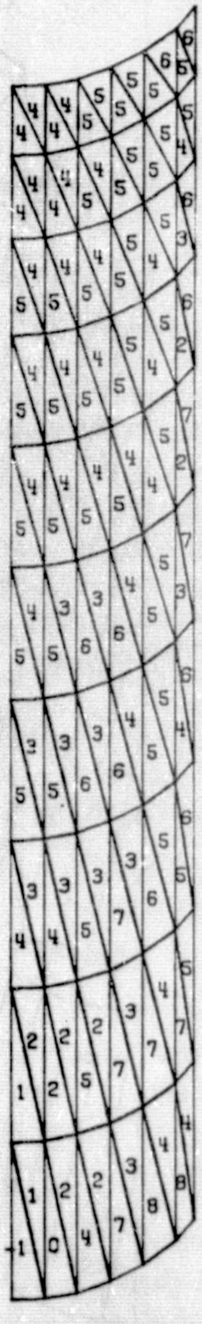
NTF ELLIP RING CONNECTED TO 41 FT CYL
KNUCKLE SECT. AT ELLIP. RING(INS. CORNE

0 27
SCALE

FIGURE 25

1/1/1

DISPLAY= PS2 /1000 , NODE= 1 , SURFACE= 0



SPEC 1.1

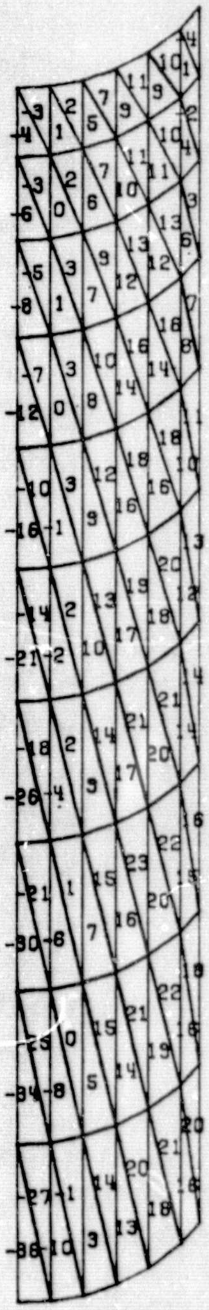
NTF ELLIP RING CONNECTED TO 41 FT CYL
KNUCKLE SECT. AT ELLIP. RING(INS. CORNE

0 SCALE 27

FIGURE 26

1/1/1

DISPLAY= PS2 /1000 , NODE= 1, SURFACE= 1



SPEC 1.1

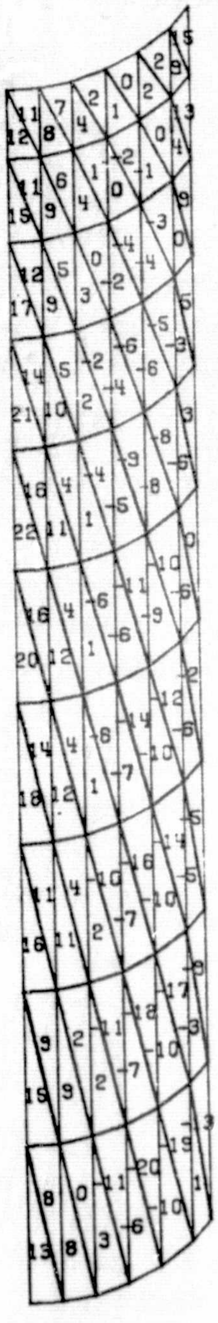
NTF ELLIP RING CONNECTED TO 41 FT CYL
KNUCKLE SECT. AT ELLIP. RING(INS. CORNE

0 ______ 27
SCALE

FIGURE 27

1/1/1

DISPLAY= PS2 /1000 , NODE= 1, SURFACE= 2



SPEC 1.1 NTF ELLIP RING CONNECTED TO 41 FT CYL KNUCKLE SECT. AT ELLIP. RING(INS. CORNE

0 SCALE 27

FIGURE 28

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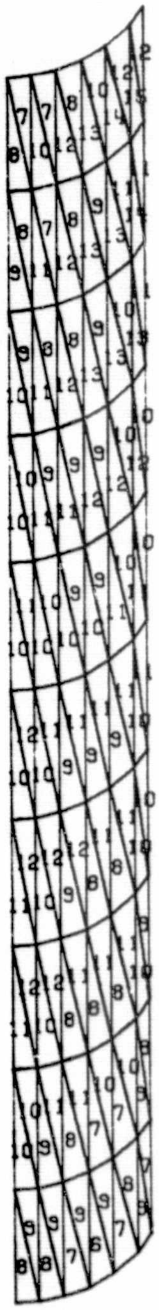
1/1/1

DISPLAY= PS1 /1000 , NODE= 1 , SURFACE= 0



SPEC 2.1

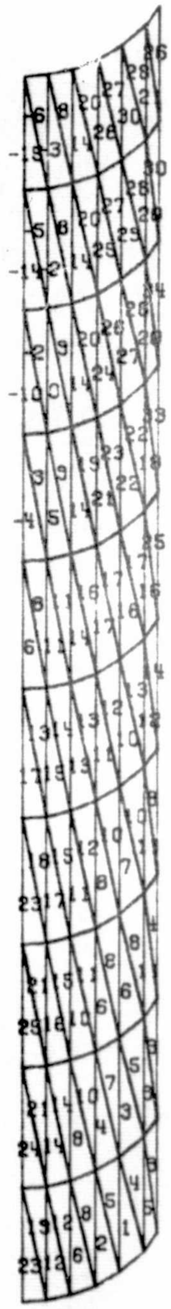
NTF ELLIP RING CONNECTED TO 41 FT CYL
KNUCKLE SECT AT ELLIP RING (MIDDLE)

0 36 SCALE

FIGURE 29

1/1/1

DISPLAY= PS1 /1000 , NODE= 1 , SURFACE= 1



SPEC 2.1

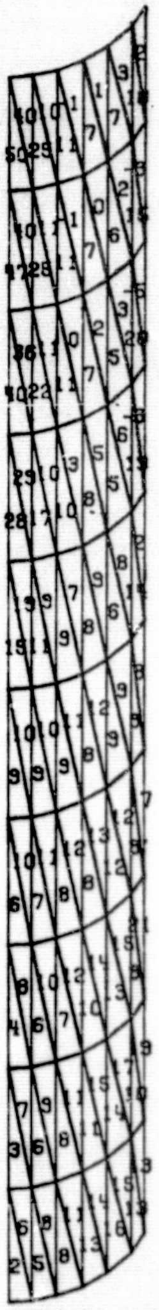
NTF ELLIP RING CONNECTED TO 41 FT CYL
KNUCKLE SECT AT ELLIP RING (MIDDLE)

0 36 SCALE

FIGURE 30

1/1/1

DISPLAY= PS1 /1000 , NODE= 1, SURFACE= 2



SPEC 2.1

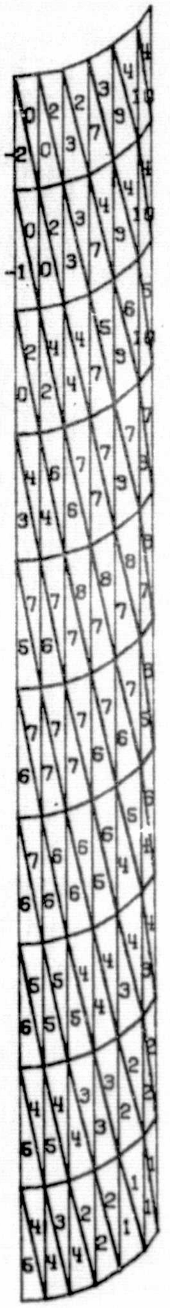
NTF ELLIP RING CONNECTED TO 41 FT CYL
KNUCKLE SECT AT ELLIP RING (MIDDLE)

0 36
SCALE

FIGURE 31

1/1/1

DISPLAY= PS2 /1000 , NODE= 1 , SURFACE= 0



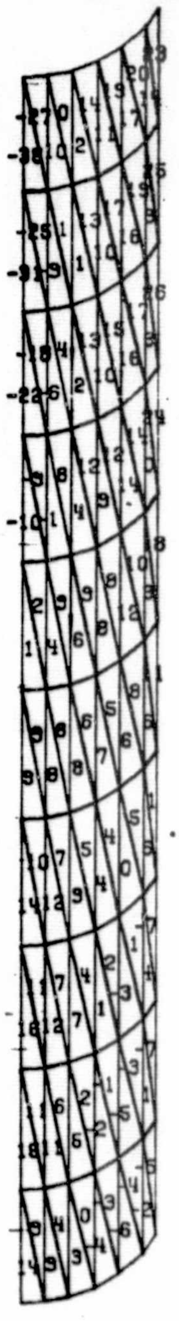
SPEC 2.1 NTF ELLIP RING CONNECTED TO 41 FT CYL
KNUCKLE SECT AT ELLIP RING (MIDDLE)

0 36
SCALE

FIGURE 32

1/1/1

DISPLAY= PS2 /1000 , NODE= 1 , SURFACE= 1



SPEC 2.1

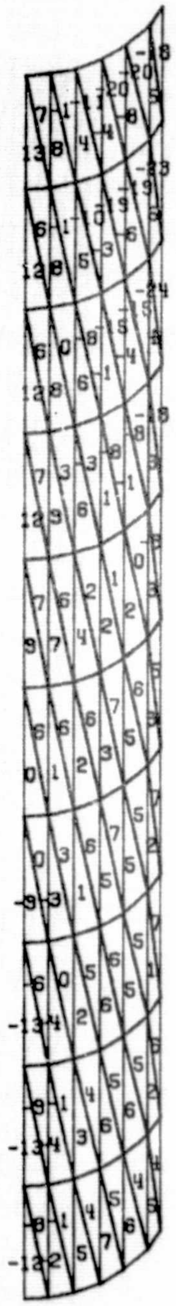
NTF ELLIP RING CONNECTED TO 41 FT CYL
KNUCKLE SECT AT ELLIP RING (MIDDLE)

0 36 SCALE

FIGURE 33

1/1/1

DISPLAY= PS2 /1000 , NODE= 1 , SURFACE= 2



SPEC 2.1

NTF ELLIP RING CONNECTED TO 41 FT CYL
KNUCKLE SECT AT ELLIP RING (MIDDLE)

0 36
SCALE

FIGURE 24

REPRODUCIBILITY OF THE
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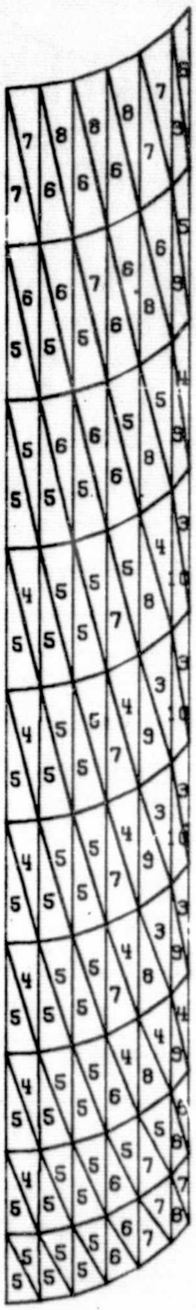
1/1/1

DISPLAY= PS1 /1000 , NODE= 1 , SURFACE= 0



SPEC 3.1

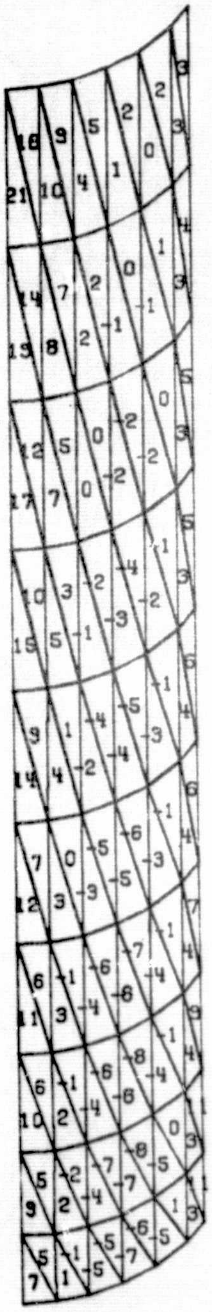
NTF ELLIP RING CONNECTED TO 41 FT CYL
KNUCK SECT AT ELLIP RING (OUTSIDE)

0 27
SCALE

FIGURE 35

1/1/1

DISPLAY= PS1 /1000 , NODE= 1 , SURFACE= 1



SPEC 3.1

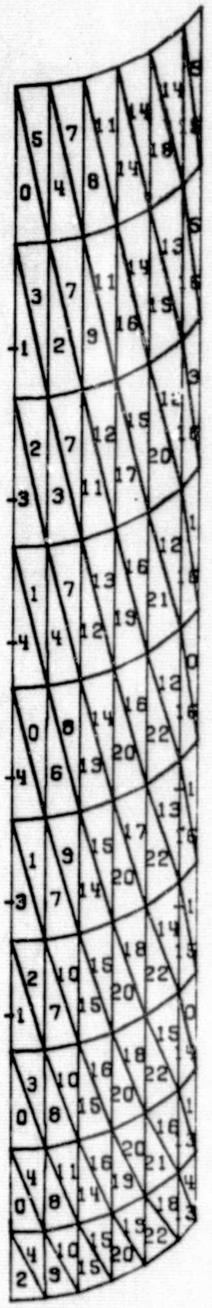
NTF ELLIP RING CONNECTED TO 41 FT CYL
KNUCK SECT AT ELLIP RING (OUTSIDE)

0 27
SCALE

FIGURE 36

DISPLAY= PS1 /1000 , NODE= 1 , SURFACE= 2

1/1/1



SPEC
3.1

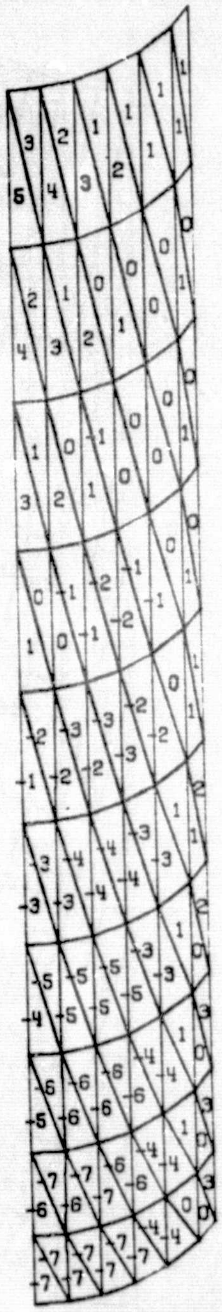
NTF ELLIP RING CONNECTED TO 41 FT CYL
KNUCK SECT AT ELLIP RING (OUTSIDE)

0 27
SCALE

FIGURE 27

1/1/1

DISPLAY= PS2 /1000 , NODE= 1 , SURFACE= 0



SPEC 3.1

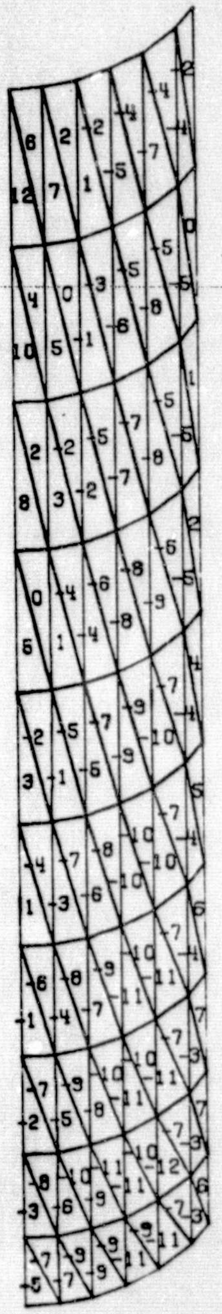
NTF ELLIP RING CONNECTED TO 41 FT CYL
KNUCK SECT AT ELLIP RING (OUTSIDE)

0 27
SCALE

FIGURE 33

1/1/1

DISPLAY= PS2 /1COC , NODE= 1, SURFACE= 1



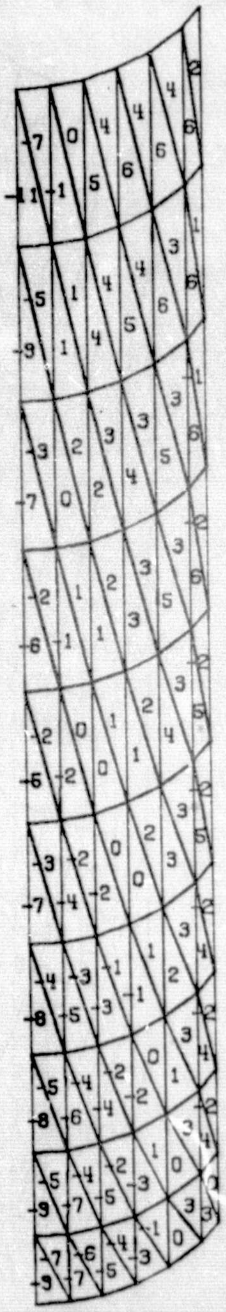
SPEC 3.1 NTF ELLIP RING CONNECTED TO 41 FT CYL
KNUCK SECT AT ELLIP RING (OUTSIDE)

0 27 SCALE

FIGURE 39

1/1/1

DISPLAY= PS2 /1000 , NODE= 1, SURFACE= 2



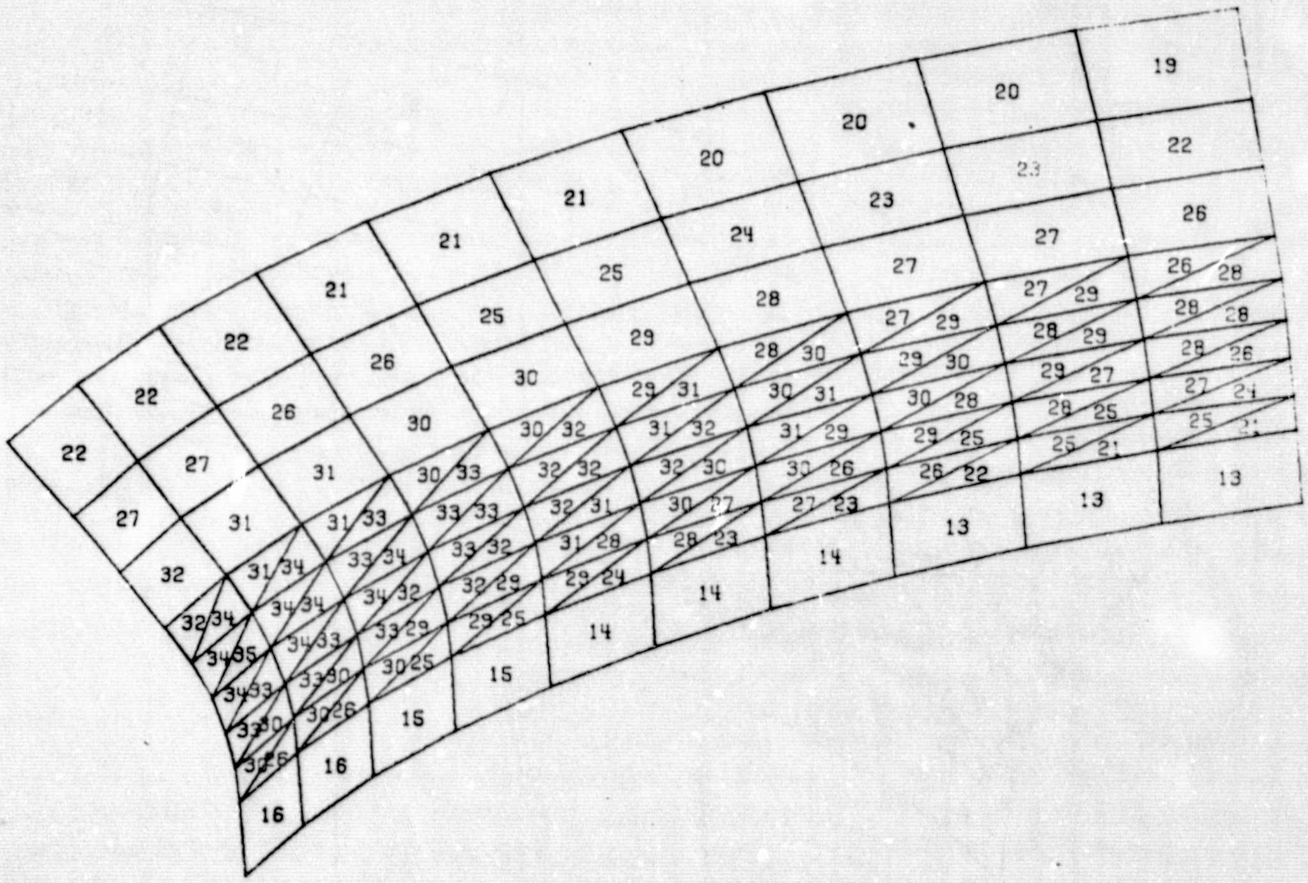
SPEC 3.1 NTF ELLIP RING CONNECTED TO 41 FT CYL
KNUCK SECT AT ELLIP RING (OUTSIDE)

0 27 SCALE

FIGURE 40

1/1/1

DISPLAY= PS1 /1000 , NODE= 1, SURFACE= 0



SPEC
4.1

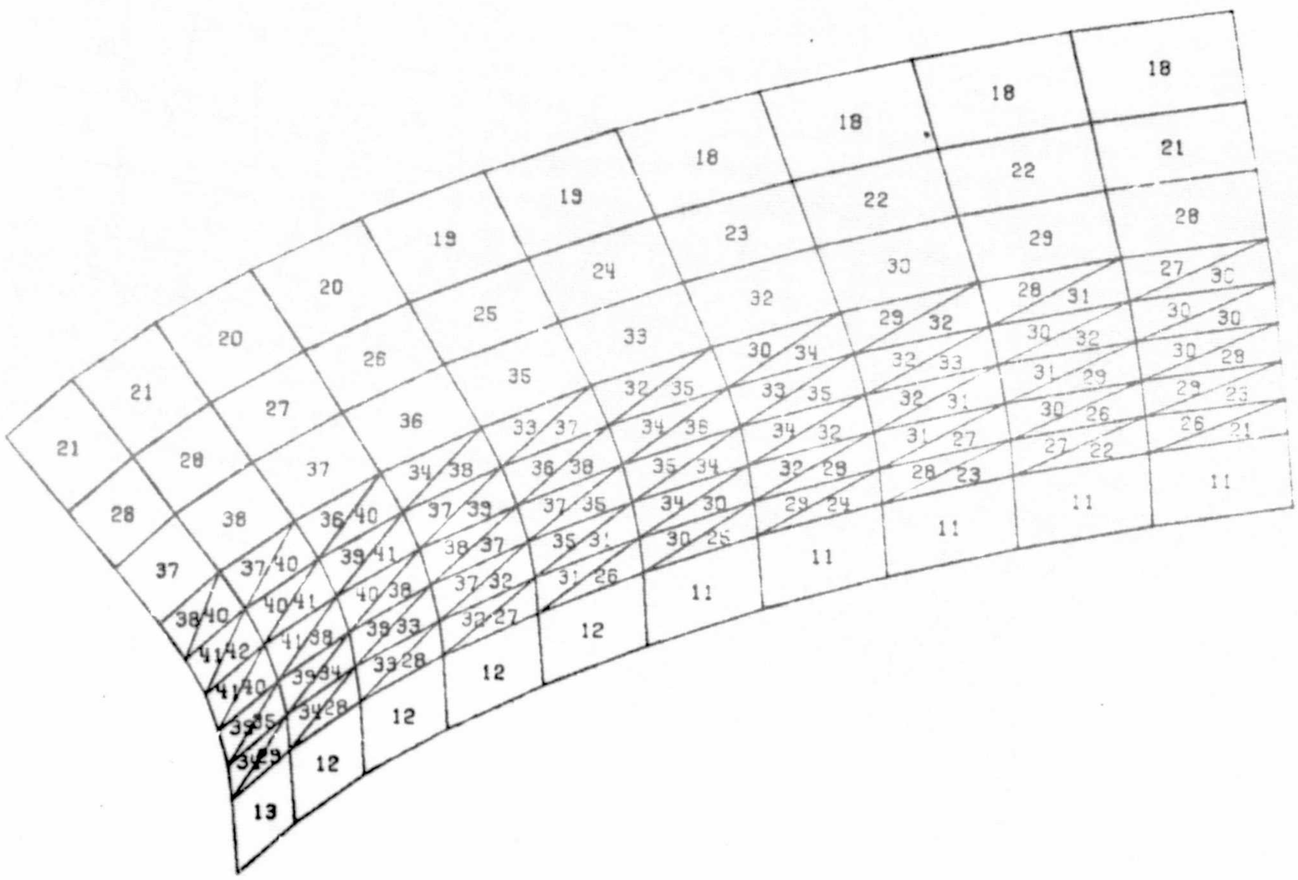
NTF ELLIP RING CONNECTED TO 41 FT CYL
CONE KNUCKLE SECTION (INSIDE CORNER)

0 23
SCALE

FIGURE 41

DISPLAY= PS1 /1000 , NODE= 1, SURFACE= 1

1/1/1



SPEC 4.1

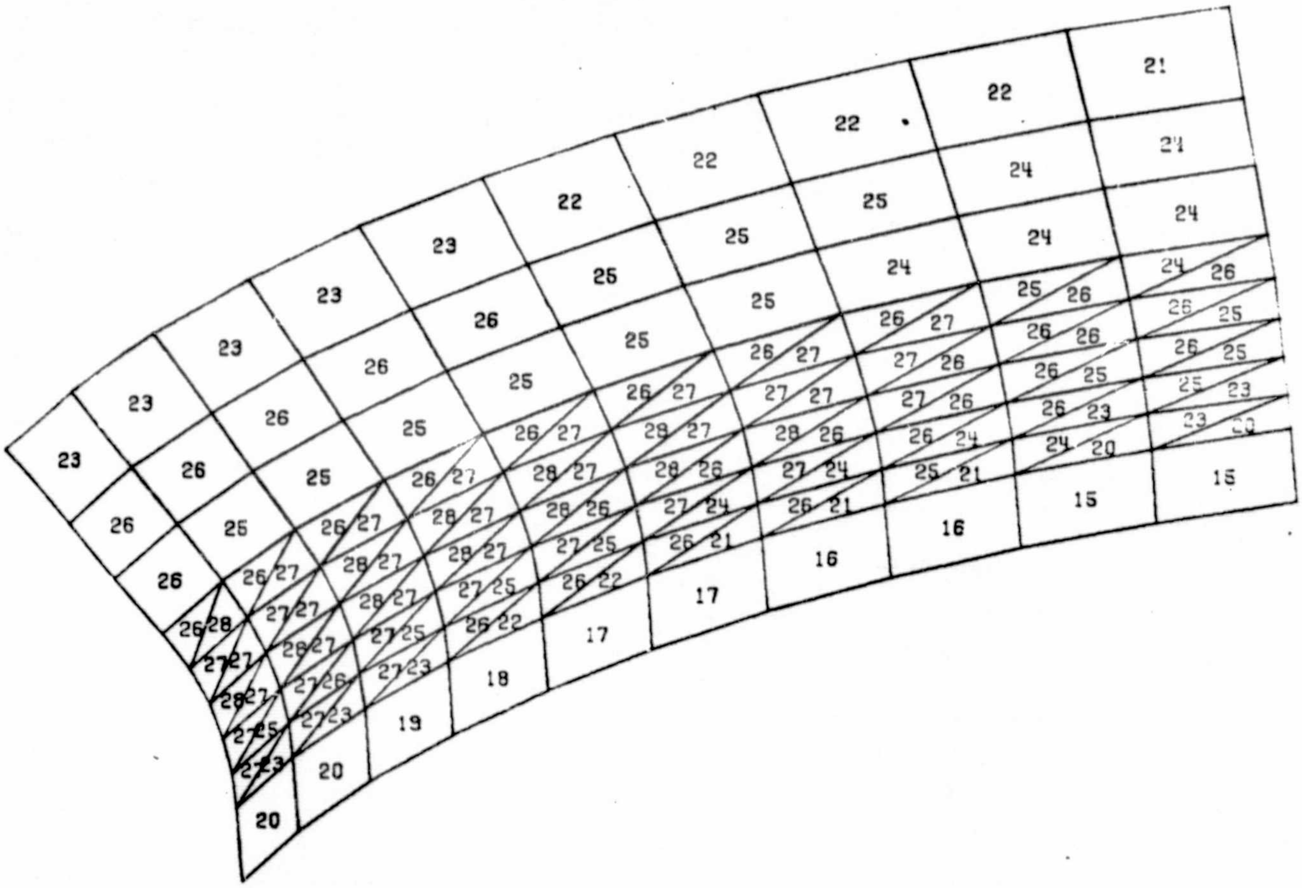
NTF ELLIP RING CONNECTED TO 41 FT CYL
CONE KNUCKLE SECTION (INSIDE CORNER)

0 23
SCALE

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

1/1/1

DISPLAY= PS1 /1000 , NODE= 1 , SURFACE= 2



SPEC
4.1

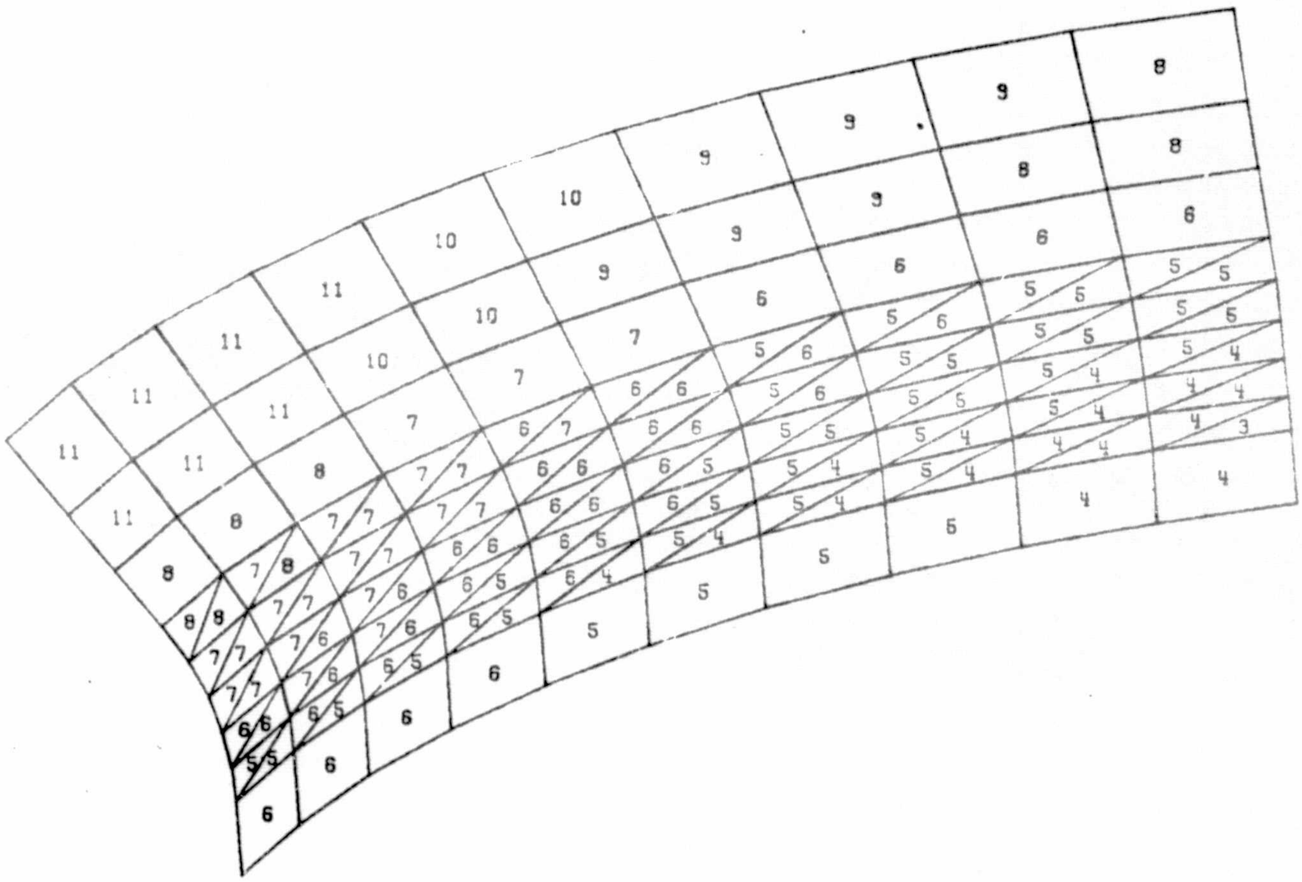
NTF ELLIP RING CONNECTED TO 41 FT CYL
CONE KNUCKLE SECTION (INSIDE CORNER)

0 23
SCALE

FIGURE 43

1/1/1

DISPLAY= PS2 /1000 , NODE= 1, SURFACE= 0



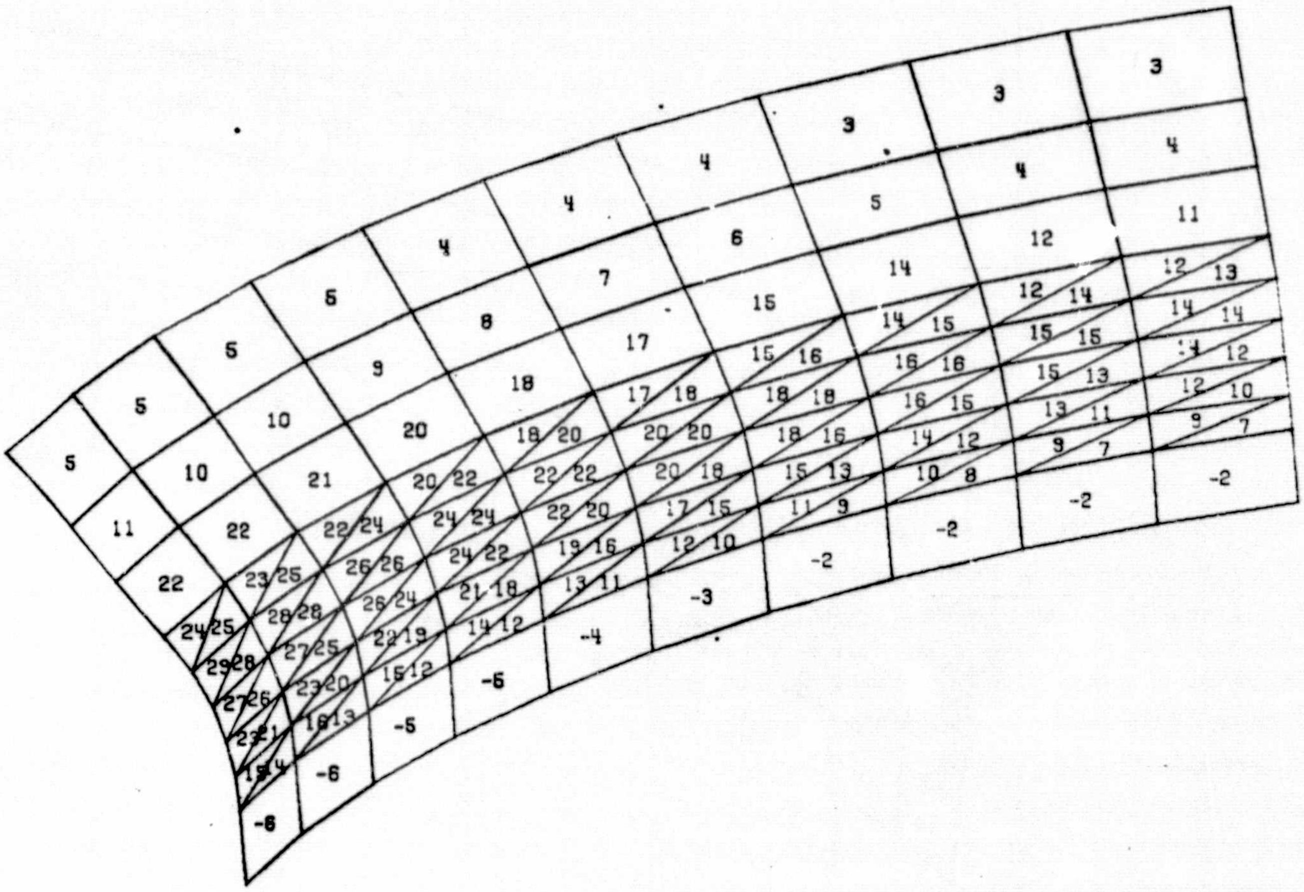
SPEC
4.1

NTF ELLIP RING CONNECTED TO 41 FT CYL
CONE KNUCKLE SECTION (INSIDE CORNER)

0 23
SCALE

FIGURE 44

DISPLAY= PS2 /1000 , NODE= 1 , SURFACE= 1

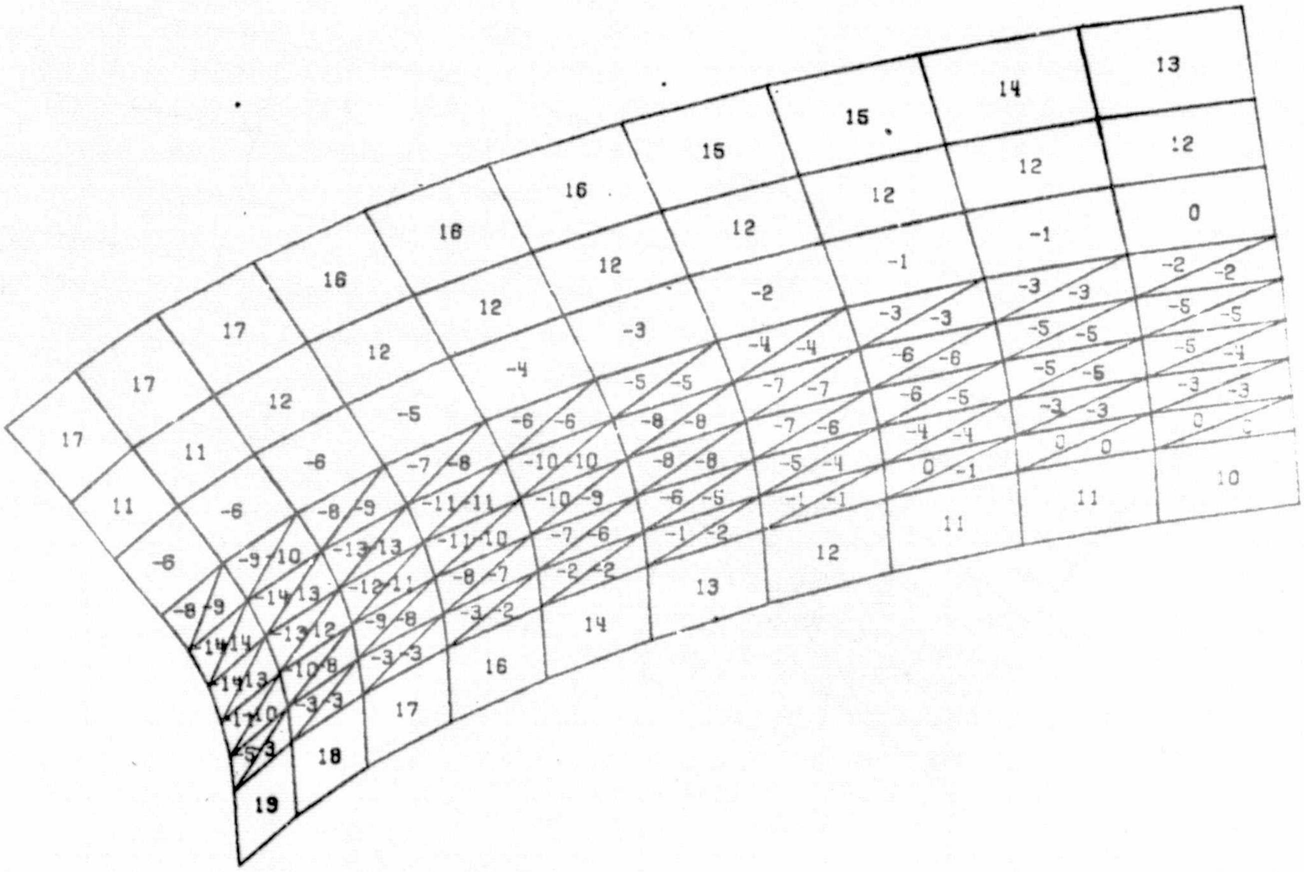


SPEC 4.1 NTF ELLIP RING CONNECTED TO 41 FT CYL
CONE KNUCKLE SECTION (INSIDE CORNER)

0 23
SCALE

FIGURE 45

DISPLAY= PS2 /1000 , NODE= 1, SURFACE= 2 1/171



SPEC 4.1

NTF ELLIP RING CONNECTED TO 41 FT CYL
CONE KNUCKLE SECTION (INSIDE CORNER)

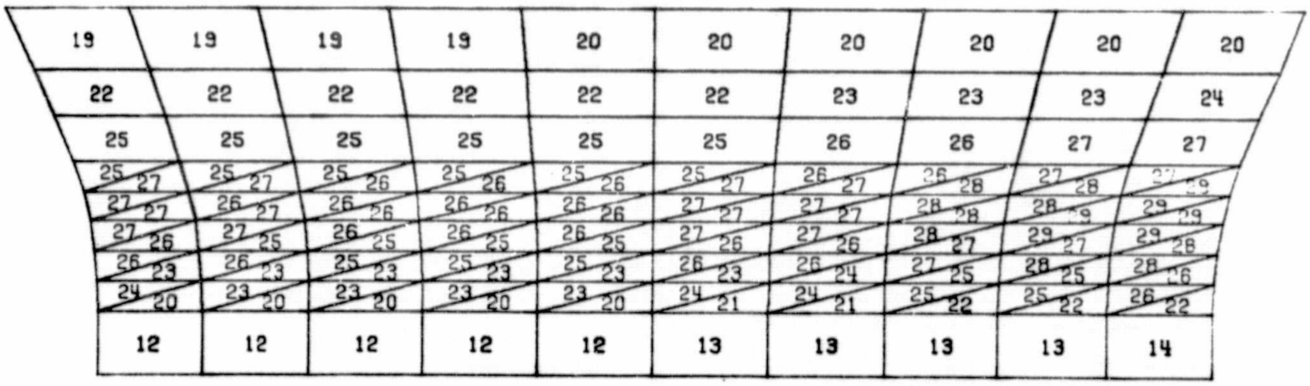
0 — 23 SCALE

FIGURE 46

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

1/1/1

DISPLAY= PS1 /1000 , NODE= 1, SURFACE= 0



SPEC 5.1

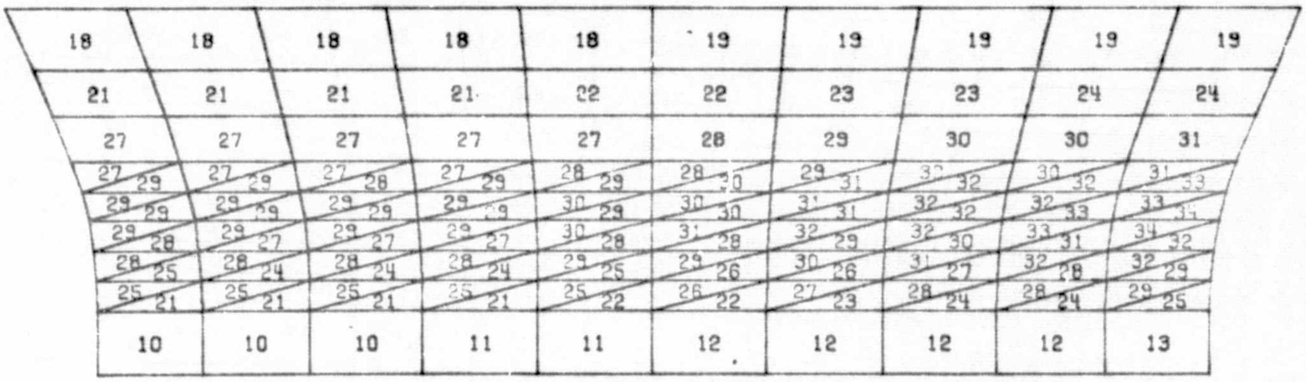
NTF ELLIP RING CONNECTED TO 41 FT CYL
CONE KNUCKLE SECT (MIDDLE)

0 28
SCALE

FIGURE 47

DISPLAY= PS1 /1000 , NODE= 1, SURFACE= 1

1/1/1



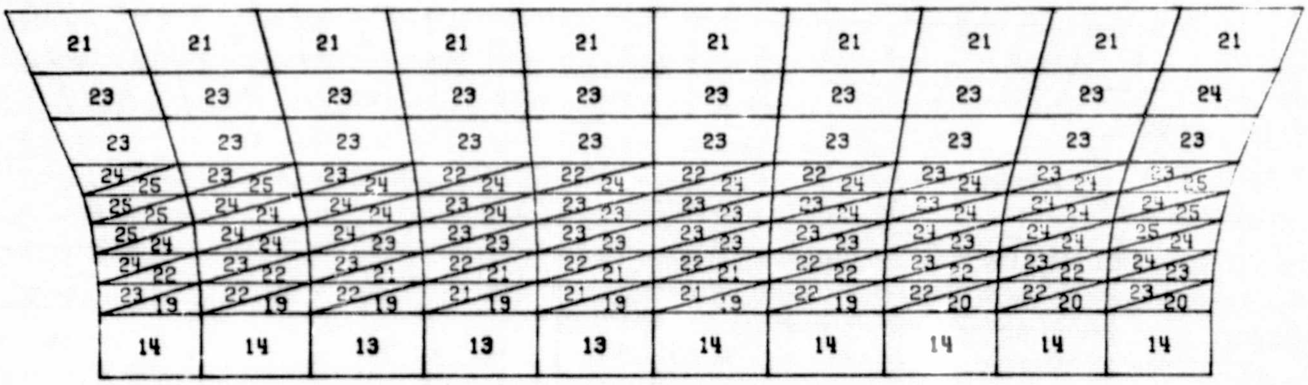
SPEC 5.1

NTF ELLIP RING CONNECTED TO 41 FT CYL
CONE KNUCKLE SECT (MIDDLE)

0 ___ 28
SCALE

FIGURE 48

DISPLAY= PS1 /1000 , NODE= 1, SURFACE= 2



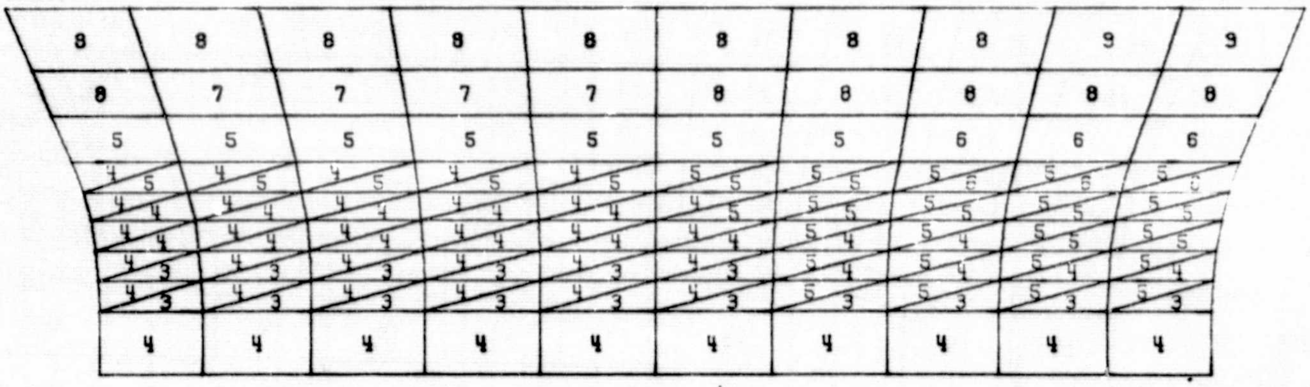
SPEC 5.1 NTF ELLIP RING CONNECTED TO 41 FT CYL
CONE KNUCKLE SECT (MIDDLE)

0 28 SCALE

FIGURE 49

DISPLAY= PS2 /1000 , NODE= 1, SURFACE= 0

1/1/1



SPEC 5.1

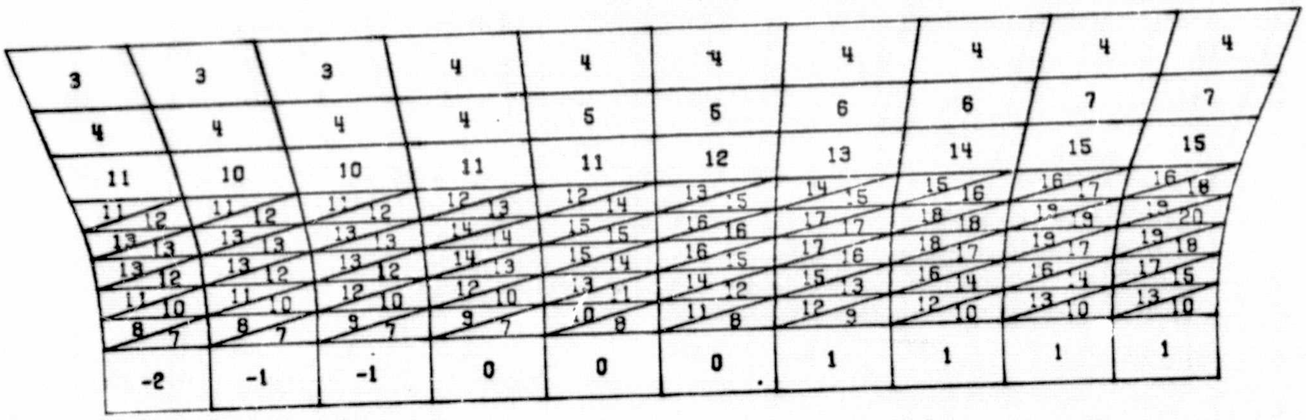
NIF ELLIP RING CONNECTED TO 41 FT CYL
CONE KNUCKLE SECT (MIDDLE)

0 .28
SCALE

FIGURE 50

1/1/1

DISPLAY= PS2 /1000 , NODE= 1, SURFACE= 1

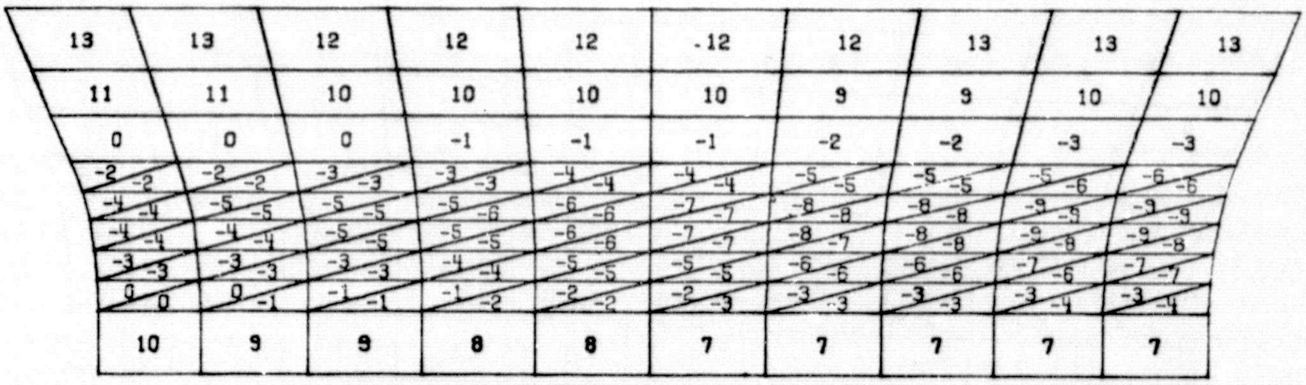


SPEC
5.1

NTF ELLIP RING CONNECTED TO 41 FT CYL
CONE KNUCKLE SECT (MIDDLE)

FIGURE 51

DISPLAY= PS2 /1000 , NODE= 1, SURFACE= 2 1/1/1



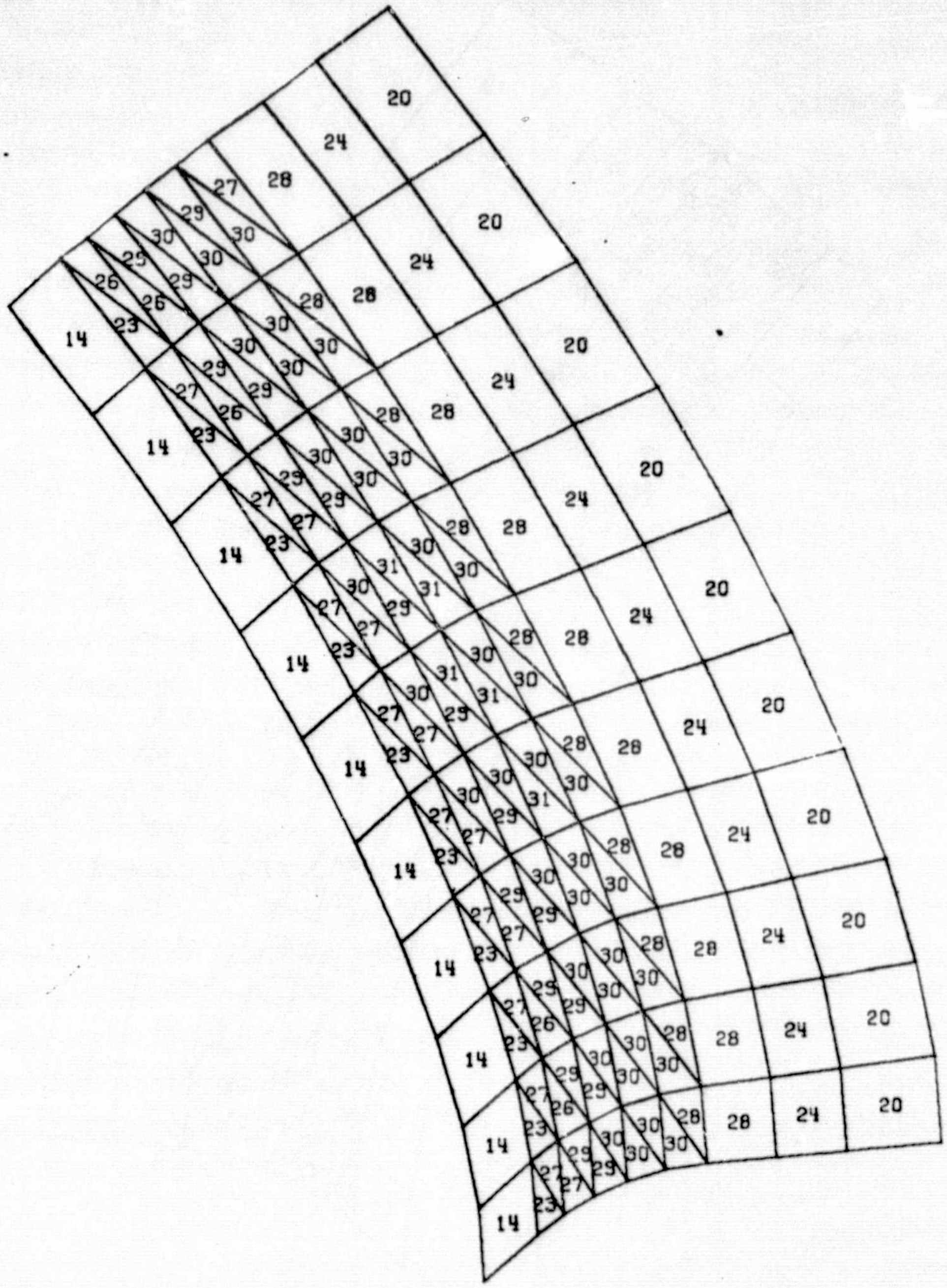
SPEC 5.1 NTF ELLIP RING CONNECTED TO 41 FT CYL
CONE KNUCKLE SECT (MIDDLE)

0 28
SCALE

FIGURE 52

1/1/1

DISPLAY= PS1 /1000 , NODE= 1, SURFACE= 0

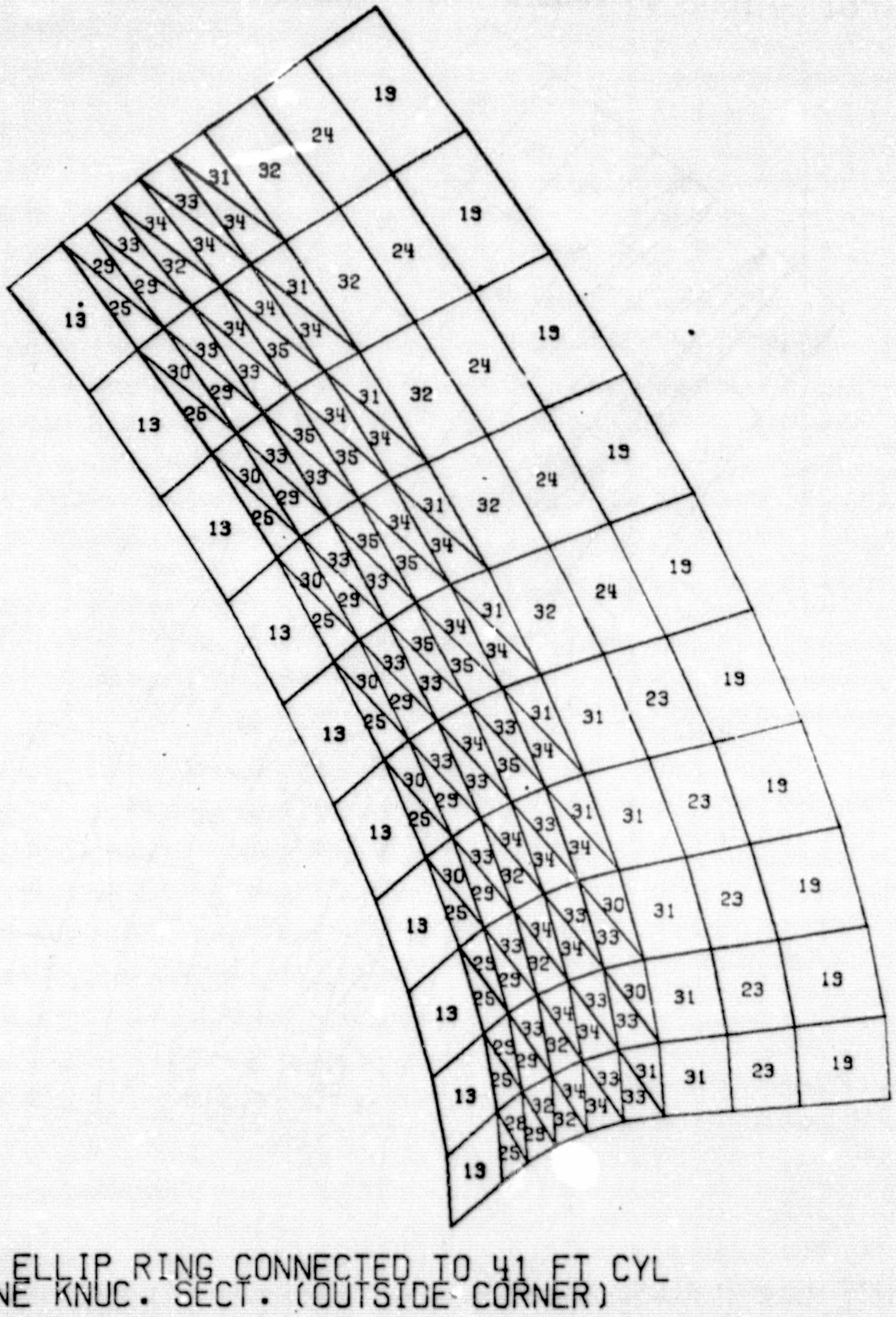


SPEC 6.1 NTF ELLIP RING CONNECTED TO 41 FT CYL
CONE KNUC. SECT. (OUTSIDE CORNER)

0 23
SCALE

FIGURE 53

DISPLAY= PS1 /1000 , NODE= 1, SURFACE= 1 1/1/1



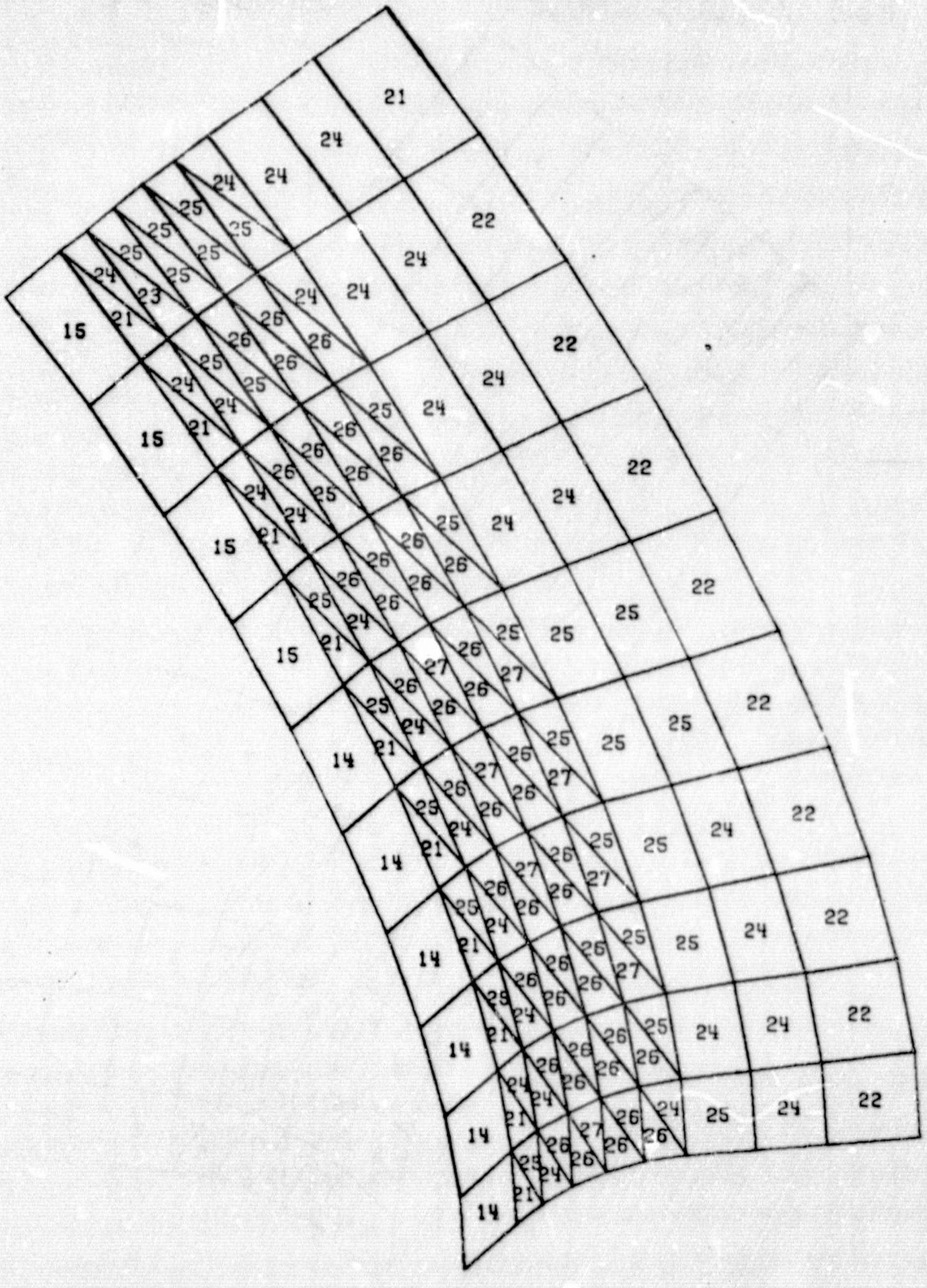
SPEC 6.1 NTF ELLIP RING CONNECTED TO 41 FT CYL
CONE KNUC. SECT. (OUTSIDE CORNER)

0 23 SCALE

FIGURE 5+

DISPLAY= PS1 /1COC , NODE= 1, SURFACE= 2

1/1/1



SPEC 6.1

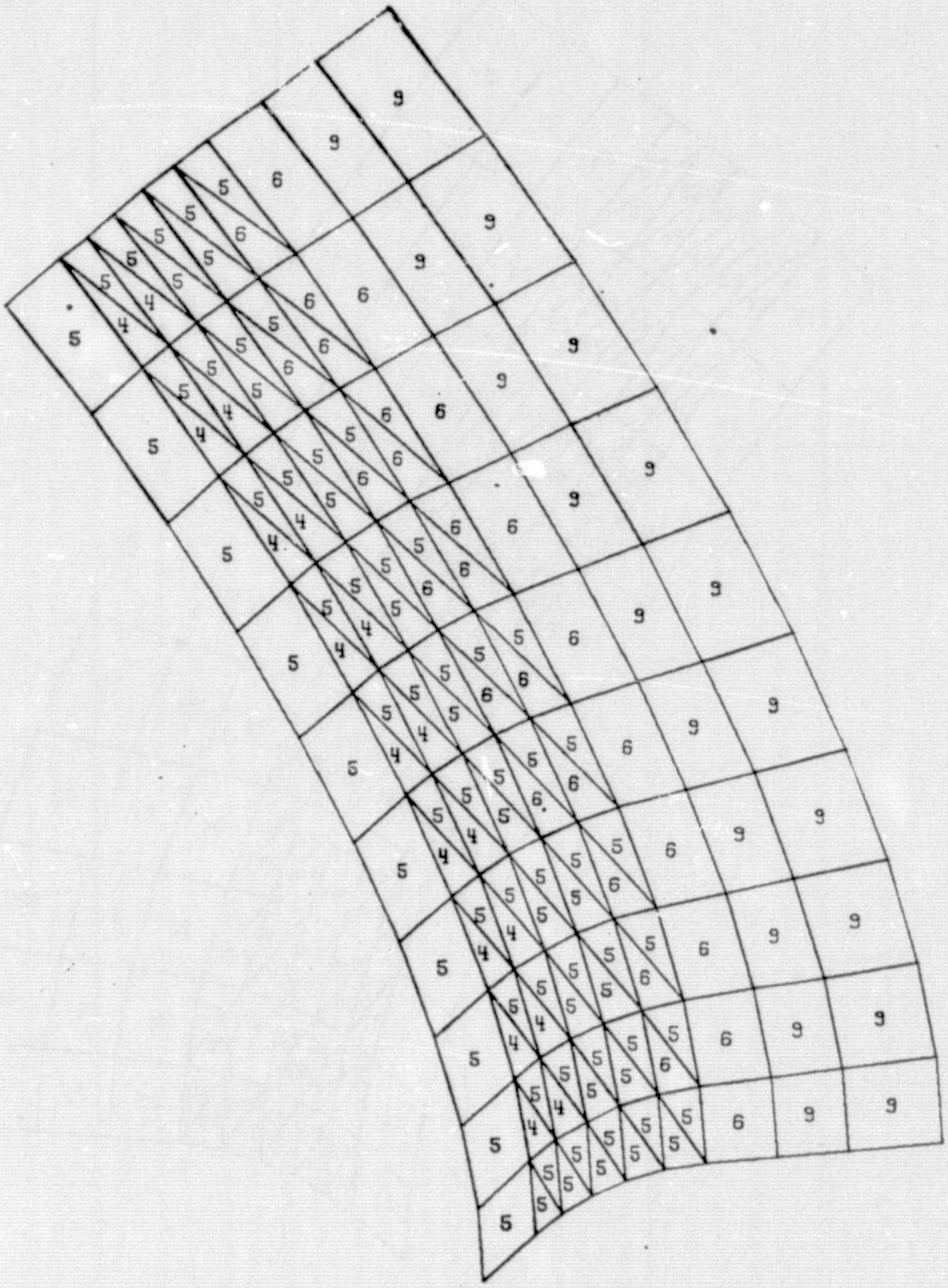
NTF ELLIP RING CONNECTED TO 41 FT CYL
CONE KNUC. SECT. (OUTSIDE CORNER)

0 23
SCALE

FIGURE 55

1/1/1

DISPLAY= PS2 /1000 , NODE= 1 , SURFACE= 0



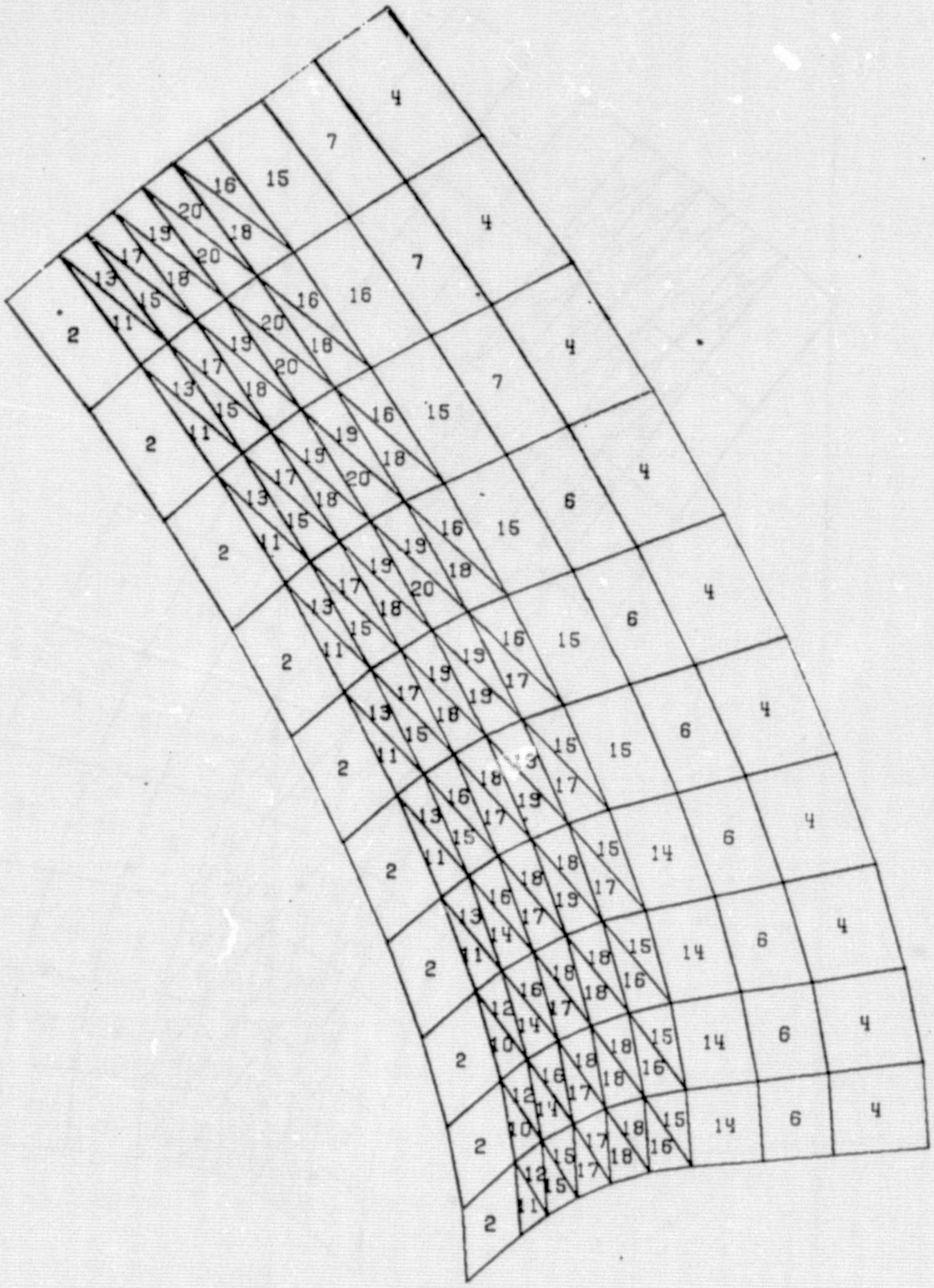
SPEC 6.1 NTF ELLIP RING CONNECTED TO 41 FT CYL
CONE KNUC. SECT. (OUTSIDE CORNER)

0 ——— 23
SCALE

FIGURE 56

1/1/1

DISPLAY= PS2 /1C00 , NODE= 1, SURFACE= 1



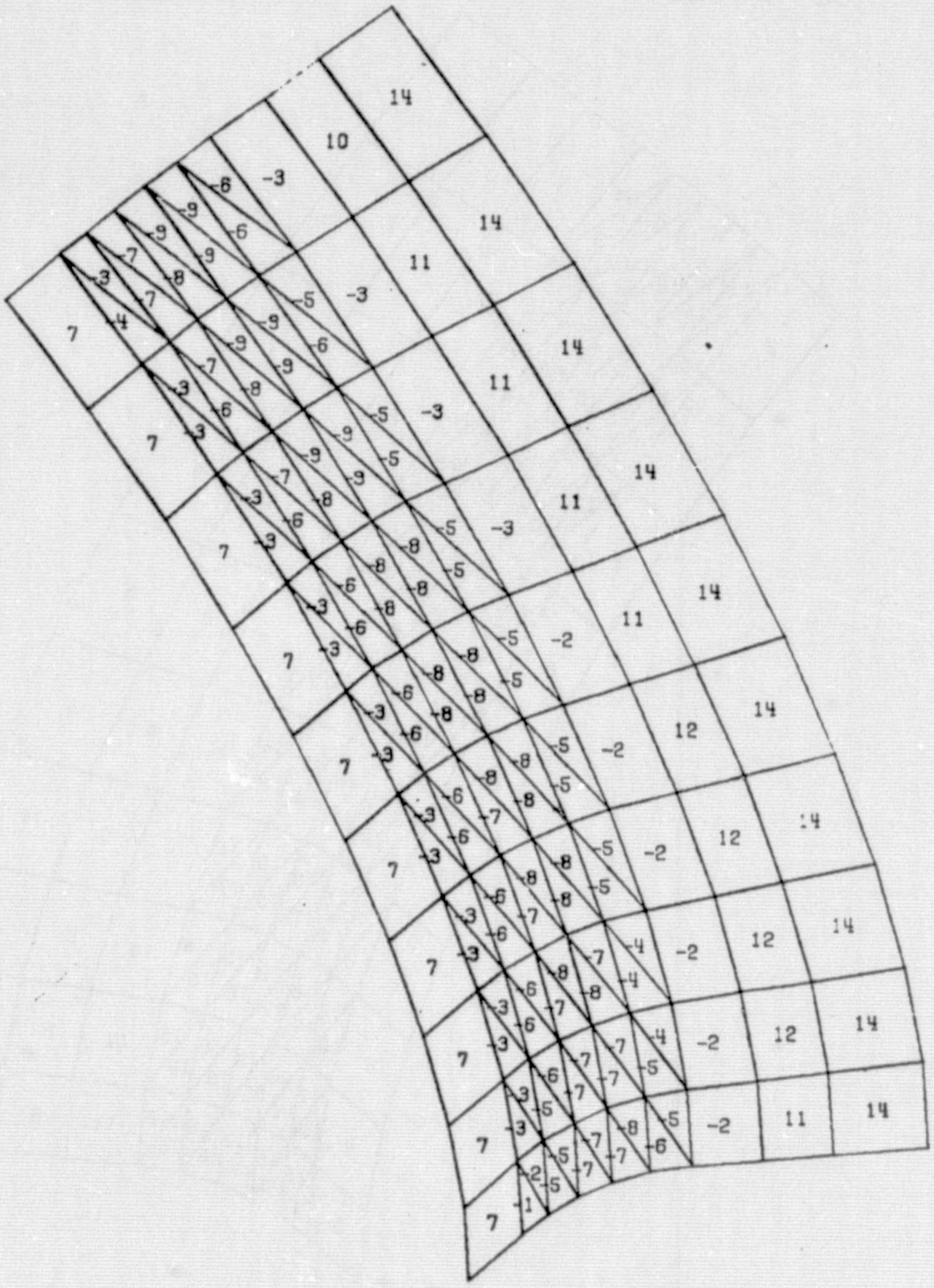
SPEC 6.1 NTF ELLIP RING CONNECTED TO 41 FT CYL
CONE KNUC. SECT. (OUTSIDE CORNER)

0 23
SCALE

FIGURE 57

DISPLAY= PS2 /1COC , NODE= 1, SURFACE= 2

1/1/1



SPEC
6.1

NTF ELLIP RING CONNECTED TO 41 FT CYL
CONE KNUC. SECT. (OUTSIDE CORNER)

0 23
SCALE

FIGURE 58

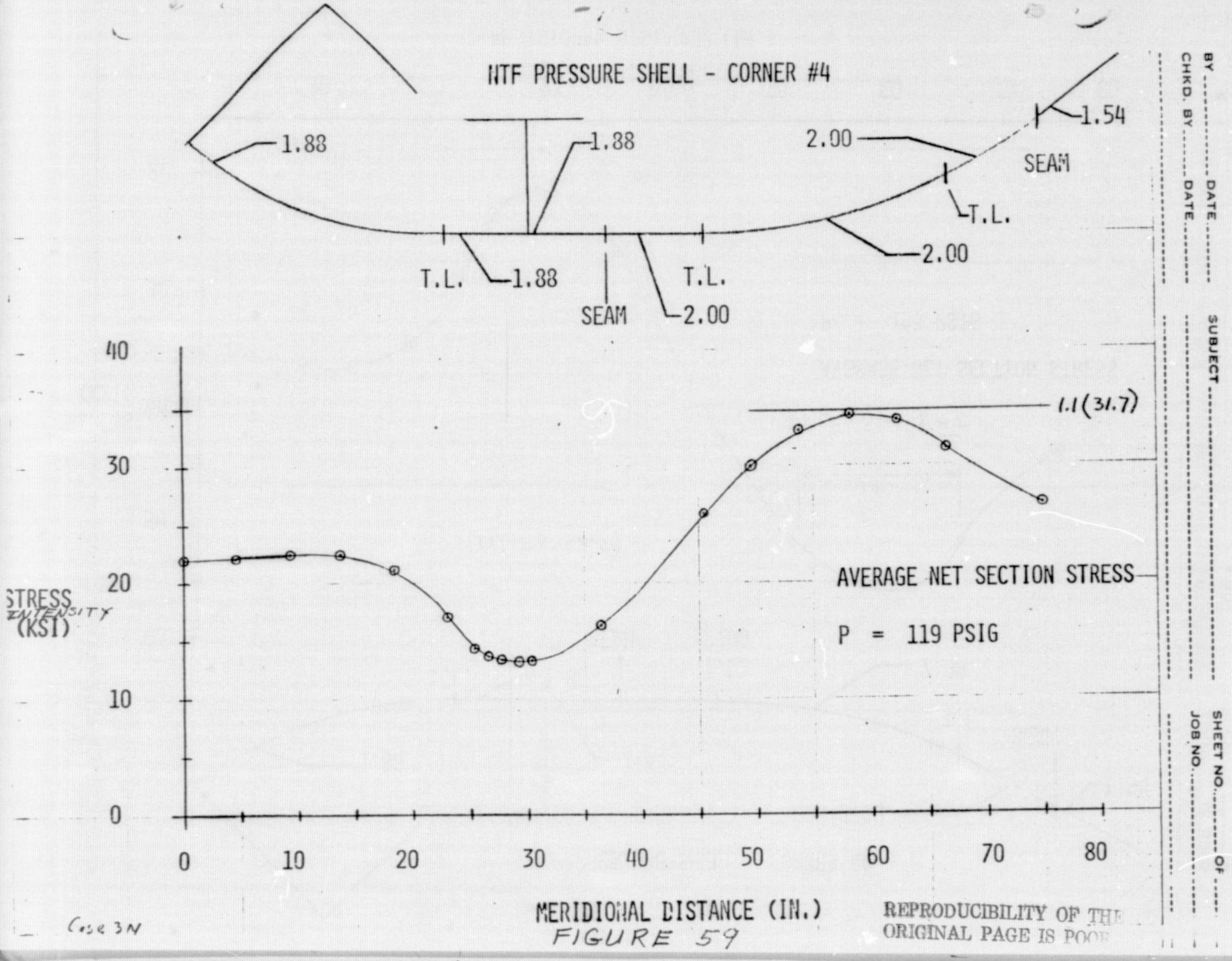
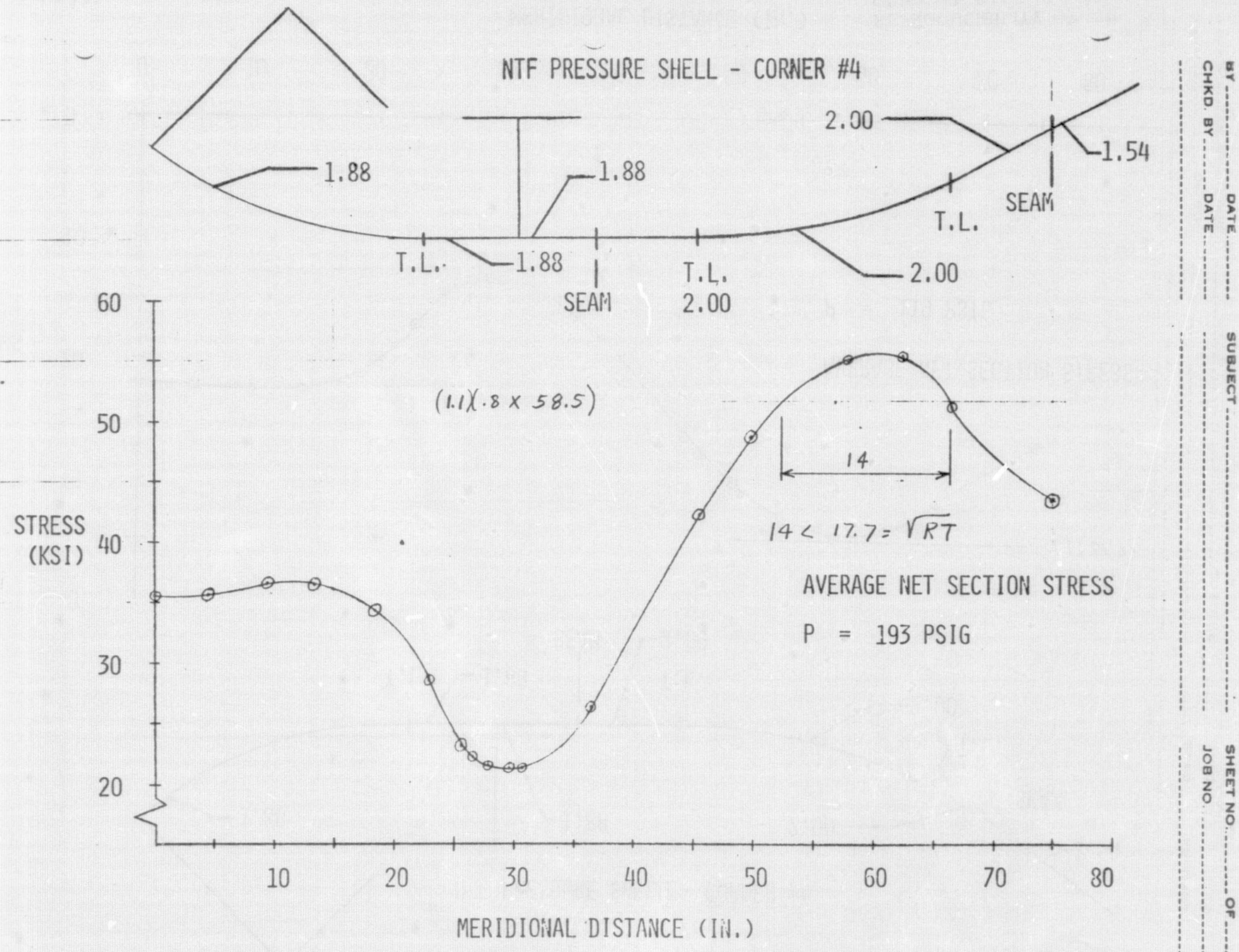


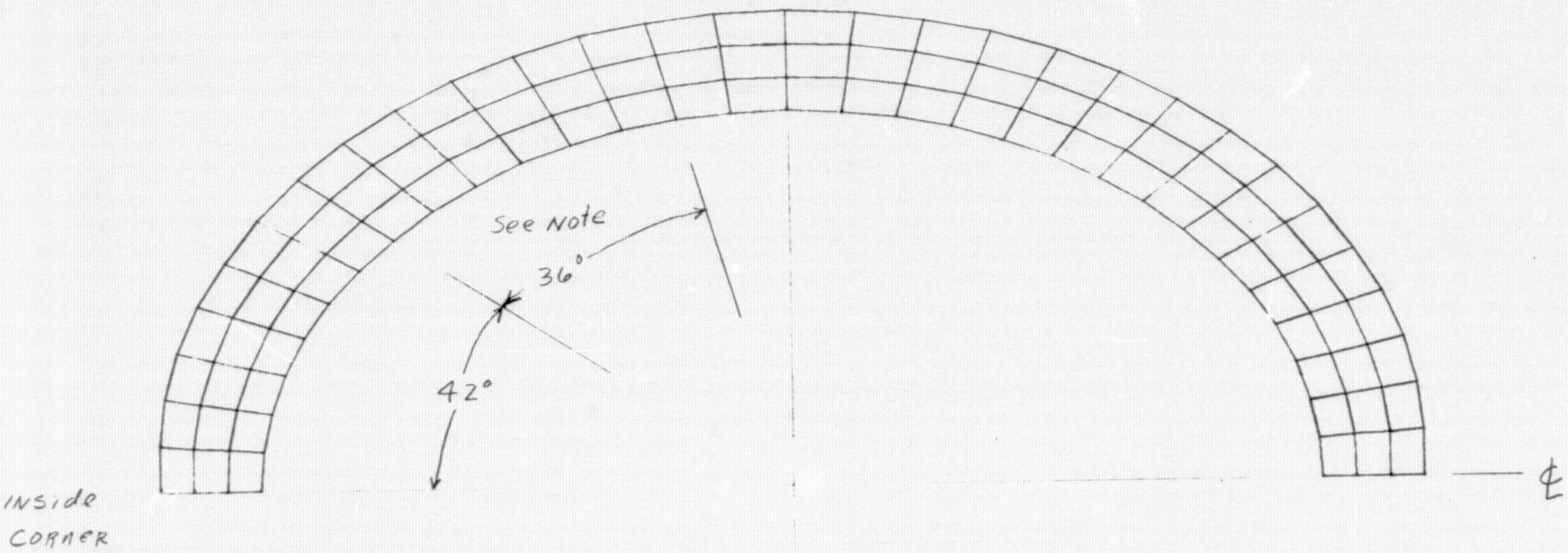
FIGURE 59

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR



NTF PRESSURE SHELL - CORNER #4
1.88
1.88
1.88
T.L.
SEAM
T.L.
2.00
2.00
2.00
T.L.
SEAM
1.54
60
50
40
30
20
STRESS (KSI)
(1.1)(.8 x 58.5)
14
14 < 17.7 = √RT
AVERAGE NET SECTION STRESS
P = 193 PSIG
10
20
30
40
50
60
70
80
MERIDIONAL DISTANCE (IN.)
BY .... DATE ....
CHKD. BY .... DATE ....
SUBJECT ....
SHEET NO. .... OF ....
JOB NO. ....

Figure 60



Note:
No longitudinal seam welds shall be located in this region of the knuckle under to "T".

0 81
SCALE

SPEC
14.1

ELLIPTICAL TEE
Looking Downstream

Figure 61